Some Aspects of the Chemistry of 1,1,1-Trihalogenoalk-4-en-2-ols, the Ene Adducts Obtained from Reaction of Chloral and Bromal with Alkenes

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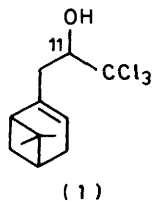
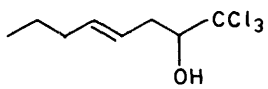
The chemistry of the title compounds has been explored and previous studies extended. They are inert to a wide range of oxidising agents, and conversion into trihalogenomethyl ketones was effected (CrO_3–H_2SO_4–AcOH) only after hydrogenation of the double bonds. Simple dehydration also failed, but the tosylate esters reacted with NaOEt–EtOH to afford ethyl alka-2,4-dienoates. Reaction of the ene adducts with alcoholic KOH gave α-alkoxy acids in high yield, as noted previously by Weizmann. A similar result was obtained with NaOR–ROH unless excess base was neutralized before work-up when α-alkoxy ester was isolated. It appears that the ester to acid conversion by the $B_{AL}2$ mechanism is relatively fast at high alkoxide ion concentrations. The trichloromethyl alcohol to α-alkoxy acid or ester conversion has been shown to occur with net retention of stereochemistry, and a mechanism based on a dichloroepoxide intermediate is proposed. The stereochemical results are accommodated by the stereoselective electrocyclic ring opening rearrangement of the dichloroepoxide. Similar considerations apply to the hydrolysis using aqueous base, when α-hydroxy acids with retention of stereochemistry were obtained; in one instance competing chloroform elimination (to give aldehyde) was observed. The dianions from the α-methoxy acids are readily converted into the corresponding β,γ-unsaturated methyl esters by oxygenation and then acidification. Reductive dehalogenation of the ene adducts by $LiAlH_4$ or Bu^n_3SnH was partially successful. The exocyclic chiral centres of the (−)-β-pinene ene adducts were detached, without loss of chirality, by oxidative degradation of the pinenyl ring; enantiometrically pure methyl (*S*)-3-acetoxy-4,4,4-trichlorobutanoate was obtained by this route.

The Lewis acid catalysed ene reactions of trihalogenoacetaldehydes with alkenes provide excellent sources of 1,1,1-trihalogenoalk-4-en-2-ols.[1] Previous work on the chemistry of trihalogenomethyl alcohols was found to be fairly limited,[2,3] and hence a series of studies was initiated with a view to exploring the synthetic utility of this functionality and also to investigate the stereochemical and mechanistic aspects of the basic chemical transformations.

The (−)-β-pinene–chloral adduct (1) and the hex-1-ene–chloral adduct (2) were selected for the most detailed study. The β-pinene adduct (1) was of particular interest as a stereochemical probe since it is available in predominantly 11(*S*)- or 11(*R*)-diastereoisomeric modifications, depending upon the conditions employed in its preparation.[4,5] The adduct (2), on the other hand, represents a simple structural type and is ideal for studies of functional group transformations. The ene addition of chloral to hex-1-ene affords a 7 : 3 mixture of (2) and the ketone (3) [1,6] which can be separated or (3) selectively destroyed with magnesium. Several other trihalogenoacetaldehyde–alkene adducts have been employed for specific purposes, and details are given in the appropriate sections.



(1)



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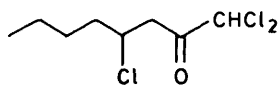
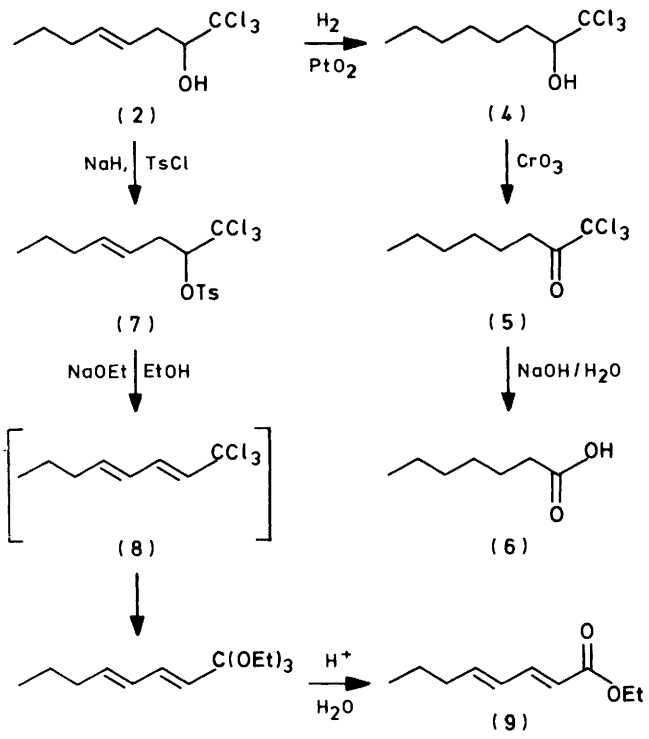


(3)

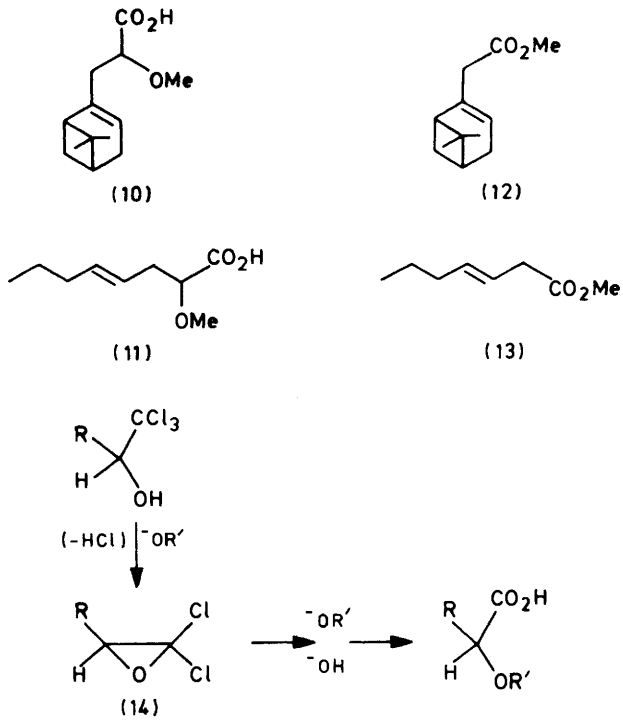
General Chemistry Relating to the OH *Group.*—The oxidation of the ene adducts to trihalogenomethyl ketones followed by cleavage with alkali would represent a cheap and convenient synthesis of allyl carboxylic acids from alkenes with allylic transposition of the double bond. Unfortunately the ene adduct (2) was unaffected by a variety of oxidising agents: these included CrO_3–H_2SO_4–AcOH, pyridinium chlorochromate, Oppenauer oxidation, and various procedures based on Kornblum-type reactions using dimethyl sulphoxide, as well as several other literature procedures for alcohol into ketone conversions. However (4), the hydrogenation product of (2), was readily oxidised to (5) in 4 h by CrO_3–H_2SO_4–AcOH. Pyridinium chlorochromate was an inefficient oxidising agent (*ca.* 30% conversion in 48 h); ruthenium tetraoxide used catalytically was more effective (*ca.* 60% conversion in 8 h). Hydrolysis of (5) by hot aqueous alkali gave heptanoic acid (6) (Scheme 1).

There are three main problems in the way of the desired alcohol into ketone conversion: (*a*) the low nucleophilicity of the OH group, (*b*) an apparently low driving force for the intended $sp^3 \longrightarrow sp^2$ hybridisation change (*e.g.* trihalogenomethyl ketones, unlike methyl ketones, form stable hydrates–presumably as a consequence of electronic factors [7]), and (*c*) steric hindrance due to the bulky CX_3 group. Within the confines of the present study only (*a*), and to some extent (*b*), are open to variation. However, treatment of the sodium salt of (2) with benzeneselenenic anhydride, in a modification of Barton and Ley's procedure,[8,9] led to recovery of (2). Likewise, treatment of (2) with trimethylaluminium then with a large excess of acetone in a modified Oppenauer oxidation, also failed to give the desired trichloromethyl ketone. Indeed, a number of other oxidants failed to oxidise the sodium salt of (2). Finally, the pyruvate ester of (2) was photolysed, according to the method of Binkley,[10] in benzene solution; prolonged irradiation merely gave the original alcohol (2).

Attempts to effect the direct dehydration of the ene adducts (1) and (2) also failed. Treatment of the sodium salt of (2),



Scheme 1.



Scheme 2.

from reaction of the alcohol with NaH in boiling ether, with toluene-*p*-sulphonyl chloride gave the tosyl ester (7) in high yield. Other ester derivatives and the α-naphthylurethane can be prepared in like manner; acetylation, however, can be effected directly by reaction of the ene adduct with Ac_2O–pyridine at room temperature, and the pyruvate ester was obtained by direct reaction with pyruvoyl chloride. These variations in reactivity emphasise the low nucleophilicity of the OH group and the importance of steric effects. Treatment of the tosyl ester (7) with sodium ethoxide in dry ethanol followed by acidic hydrolysis afforded the dienoic ester (9), presumably by way of the intermediate product (8) (Scheme 1). Similarly, (1)-tosylate was converted into ethyl 3-{1*S*,5*S*)-6,6-dimethylbicyclo[3.1.1]hept-2-en-2-yl}prop-2-enoate.

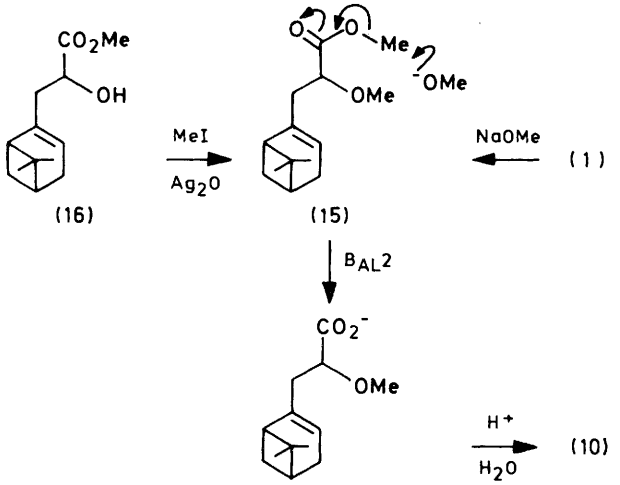
Reaction of Trichloromethyl Alcohols with Base.—In 1948 Weizmann [3] reported that reaction of a series of saturated trichloromethyl alcohols with potassium hydroxide in alcoholic solution at reflux gave rise to near quantitative yields of α-alkoxy acids. Reaction of ene adducts (1) and (2) with KOH–MeOH gave (10) and (11) in excellent yield. Treatment of these α-methoxy acids with 2 mol equiv. of lithium diisopropylamide followed by oxygenation and then acidification [11] afforded, respectively the β,γ-unsaturated esters (12) and (13) in 25 and 40% yield after chromatographic purification. In some respects this route provides a way round the problem of direct ene adduct oxidation discussed above.

Weizmann *et al.*[3] considered that the conversion of trichloromethyl alcohols into α-alkoxy acids by alcoholic KOH proceeded by way of dichloroepoxide intermediates (Scheme 2). This followed upon a much earlier suggestion by Jocic for the related reaction with aqueous alkali which affords α-hydroxy acids.[12] Reeve *et al.*[13] have reinvestigated the conversion of phenyl(trichloromethyl)methanol into α-chlorophenylacetic acid under Jocic conditions, but of several mechanisms considered not one accounted for all of the experimental facts.

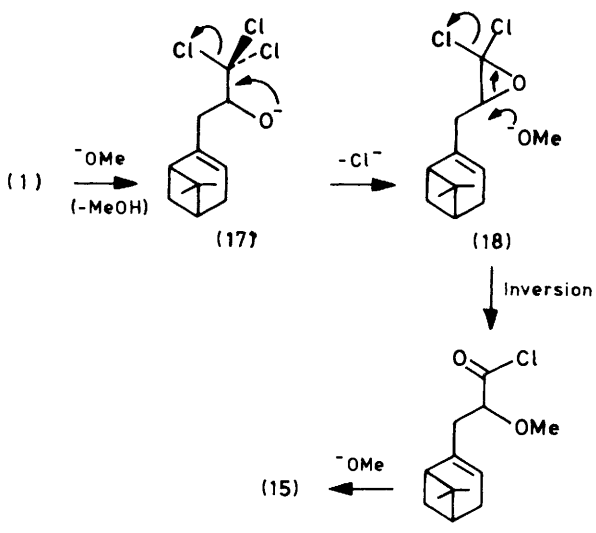
The solvolytic cleavage of X-substituted cyclopropanes (X = leaving group) to give allylic compounds are known, from rate data, to be highly stereoselective processes. With appropriate substitution of the three-membered ring only one of the two possible disrotatory modes of cleavage is found to occur.[14] The thermal or acid or base catalysed rearrangement of α-chloroepoxides to α-chloro-aldehydes or -ketones is a well-known process. Recently, McDonald [15a] concluded, on the basis of kinetic data and Hammett correlations, that *trans*-β-chlorostyrene oxides rearrange thermally to phenylchloroacetaldehydes by disrotatory C_β–O bond heterolysis to yield the corresponding α-ketocarbonium-chloride ion pairs. The stereochemistry of the reaction was not determined, but stereospecific C–Cl bond formation in the α-chlorocarbonyl products in cyclic [15b] and bicyclic [15d] examples had been reported previously. In these cases the Cl^- migrated from one face of the α-chloroepoxide to the opposite face to yield the α-chloroketone product (*i.e.* from *endo* to *exo* faces in the norbornyl system [15c]).

Several reactions were conducted at essentially zero OH^- concentrations by stirring the ene adducts (1) and (2) in solutions of sodium methoxide in dry methanol or sodium ethoxide in dry ethanol for 48 h at room temperature. Removal of the bulk of the alcohol under reduced pressure prior to quenching with dilute acid and extraction of the product, as in the alcoholic KOH procedure, also gave the α-alkoxy acids, *e.g.* (10) and (11) from NaOMe–MeOH treatment of (1) and (2) respectively. However, α-alkoxy esters are the primary reaction products and can be isolated from the alkoxide–alcohol reactions (provided that the reaction mixtures are not boiled) by neutralising the base prior to solvent removal; only traces of α-alkoxy acids were then detected. Presumably the ester into acid conversion occurs at high alkoxide ion concentrations by a $B_{AL}2$ mechanism (Scheme 3). The mechanism may also operate in the KOH–ROH reactions since the equilibrium $ROH + {}^-OH \rightleftharpoons RO^- + H_2O$ is shifted to the right in the presence of a large excess of alcohol.

Separate samples of the α-methoxy methyl ester (15) were



Scheme 3.



Scheme 4.

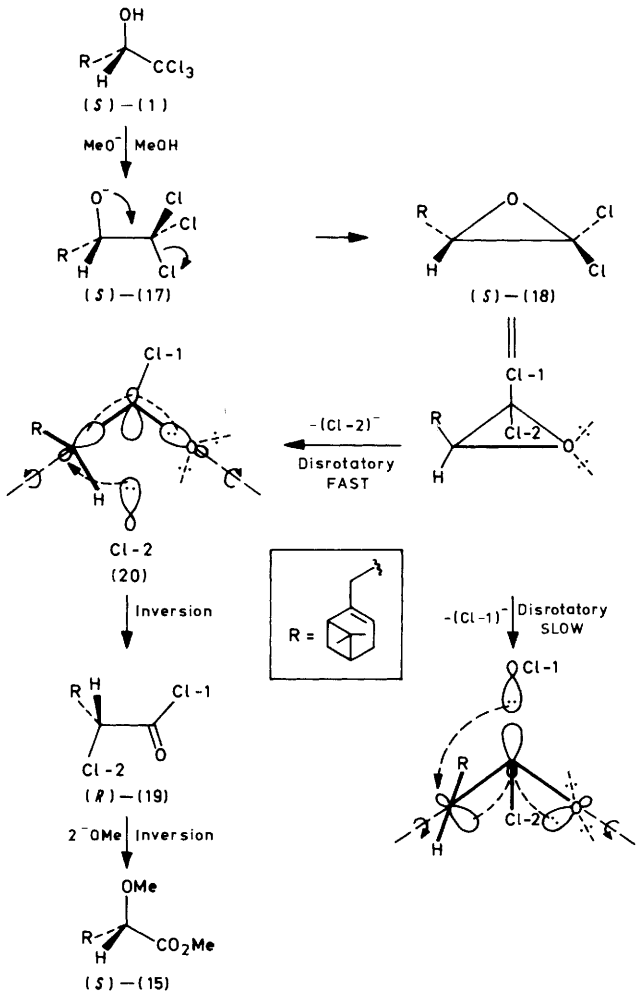
Table. Summary of the results indicating that the conversion (1) ⟶ (15) occurs with net retention of stereochemistry

Starting material		Reaction product (15)		Effect [a] of Eu(fod)$_3$ on
Origin	11(*S*) : 11(*R*)	$[\alpha]_D^{24}$ (°)	11(*S*) : 11(*R*)	sample of (15)
(1) [b]	76 : 24	−8	75 : 25	major
(1) [c]	17 : 83	−41	17 : 83	minor
(16) [d]	*ca.* 15 : 85	−42	15 : 85	minor

[a] That diastereoisomer (major or minor) of the two present in compounds (15) whose signals were shifted downfield more rapidly upon addition of Eu(fod)$_3$ is indicated. [b] From the $AlCl_3$-catalysed ene addition of chloral to (−)-β-pinene. [c] From the thermal addition of chloral to (−)-β-pinene. [d] See text.

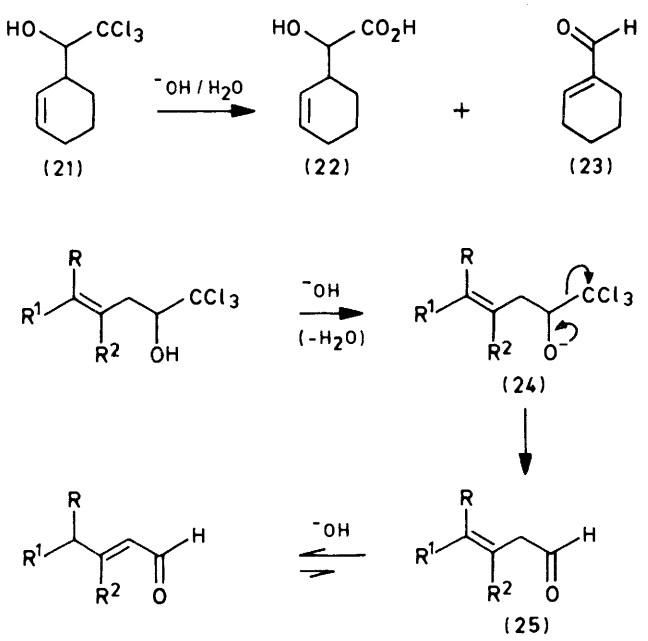
prepared by the above method using NaOMe–MeOH starting from samples of (1) of different diastereoisomeric composition.[4,5] The diastereoisomeric ratios of (15) were determined from Eu(fod)$_3$ shifted ^{1}H n.m.r. spectra in which pairs of signals were resolved for OCH_3, CO_2CH_3, and =CH protons and the H atoms at the chiral centres C-11. For comparison purposes a sample of predominantly 11(*R*)-(15) was also prepared by an independent route. The ene adduct (16), from $AlCl_3$ catalysed addition of methyl glyoxylate to (−)-β-pinene, of *ca.* 85 : 15 11(*R*) : 11(*S*) composition [16] was converted into (15), without change in stereochemistry, by treatment with a suspension of silver(I) oxide in methyl iodide. Comparison of the Eu(fod)$_3$ shifted ^{1}H n.m.r. spectra of the various samples of (15) showed conclusively that conversion of (1) into (15) was completely stereoselective and had occurred with net *retention* of stereochemistry. Additional proof was provided by optical rotation measurements; the results are summarised in the Table.

Weizmann *et al.*[3] considered that the initially formed dichloroepoxide intermediate was converted into the α-alkoxy acid by way of the α-lactone. This mechanism must now be considered disproven because it predicts inversion of configuration at the α-carbon atom, and a similar conclusion applies to the direct transformation of the dichloroepoxide outlined in Scheme 4. The stereochemical results can be accommodated by a double inversion process at C-11, leading to overall retention of stereochemistry, as outlined in Scheme 5 for (*S*)-(1). The essential feature of this mechanism is the proposed rapid stereoselective intramolecular rearrangement of the dichloroepoxide intermediate (18) to the α-chloro acid



Scheme 5.

chloride (19) which involves inversion at C-11. The subsequent reaction of (19) with methoxide ion accounts for the second inversion, and is unexceptional. Stereoselectivity arises through the greater solvolytic reactivity of Cl-2 whose ionis-



Scheme 6.

ation is anchimerically assisted by the specific disrotatory cleavage that rotates the bulky α-pinenyl group outwards. This allows the tight ion pairing within the solvent cage between $(Cl\text{-}2)^-$ and the oxa-allyl carbonium ion (20), and recombination by bonding of Cl^- to C-11 results in the first inversion of stereochemistry. The migration of Cl^- to the opposite face in McDonald's [16b-d] cyclic and bicyclic α-chloroepoxide rearrangements is presumably due to conformational and stereoelectronic effects which results in the diffusion apart of the original ion pairs. The complete racemisation during intramolecular chlorine migration in the conversion of (*R*)-(−)-phenyl(trichloromethyl)methanol to α-chlorophenylacetic acid by cold aqueous KOH [13] may be due to the stabilisation of the oxa-allyl carbonium ion by the phenyl substituent, resulting in the diffusion apart of the original ion pairs, and in consequence giving non-stereospecific reaction upon ion pair return. These additional stereoelectronic or conformational contributions are absent in the present systems, and hence the oxa-allyl carbonium ions are rapidly quenched by Cl^- with complete stereospecificity.

We sought next to clarify the nature of the aqueous base hydrolyses of trichloromethyl alcohols such as (1) and (2). Hydrolysis of (2) under Jocic conditions (*i.e.* 10% aqueous KOH, 0 °C) was extremely slow, and the hydrolysis product appeared to be (27) rather than the α-chloro acid. The hydrolysis conditions employed by Colonge and Perrot [2] (*i.e.* boiling dilute aqueous Na_2CO_3 or NaOH) were only partially successful. Hydrolyses of (1) and (2) were very slow and appreciable quantities of starting materials remained even after 6 h. The acidic products consisted of complex mixtures of acids, hydroxy acids, and lactones, and the absence of olefinic proton signals in the ^1H n.m.r. spectra suggests that the double bonds participated in the reactions. Traces of aldehydes were identified in the neutral fractions from both processes. Hydrolysis of the cyclohexene-chloral adduct (21), the pure (*R*,*R*) + (*S*,*S*) diastereoisomer, proceeded satisfactorily under the same conditions and afforded (22) and (23) in 24 and 38% isolated yields, respectively. The isolation of aldehydes such as (23), while ignoring the α-hydroxy acids such as (22), was presumably a major factor that led Colonge and Perrot to formulate the original olefin/chloral adducts as alk-3-enes rather than as ene adducts (alk-4-enes). These aldehydes most probably arise by the mechanism outlined in Scheme 6, the double bond migration in (25) occurring after the elimination of chloroform from intermediate (24) The α-hydroxy acid (22) was a solid, and presumably a single diastereoisomer. Because of the possibility of diastereoisomer fractionation in the isolation of crystalline material, this result cannot be used to infer that the hydrolysis by aqueous base was a stereospecific process.

The most satisfactory and general procedure we have found for the preparation of α-hydroxy acids such as (26) and (27) from adducts (1) and (2) involves the use of a two-phase system and a phase-transfer catalyst (*i.e.* 50% aqueous NaOH, CH_2Cl_2, triethylbenzylammonium chloride, 6 h at room temperature). The desired α-hydroxy acids were normally the exclusive products, and were isolated in yields of up to 40%. Occasionally, however, (27) was contaminated with (28), which probably arises from dehydrochlorination of an α-chloro acid chloride intermediate. A 76 : 24 mixture of 11(*S*)-(1) : 11(*R*)-(1) [4,5] was hydrolysed to the α-hydroxy acid (26) which was treated, without purification, with diazomethane to give the α-hydroxy methyl ester (16). G.l.c. analysis of this sample of (16) on a 50 m Carbowax 20M glass capillary column, in comparison with samples of (16) of known diastereoisomer composition originating from methyl glyoxylate–(−)-β-pinene ene additions,[16] established that the 11(*S*)-(16) :

11(*R*)-(16) ratio was 76 : 24. The hydrolysis of (1) by aqueous base, therefore, occurs with retention of stereochemistry. It seems unlikely in view of the previous results, discussed above, that (26) arises from (1) by direct attack on the CCl_3 group by OH^-, but rather the mechanism is essentially that of Scheme 5 with replacement of methoxide by hydroxide ion.

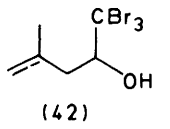
All attempts to isolate a dichloroepoxide intermediate from these base hydrolysis reactions, or to prepare such a compound by an independent route, have proven unsuccessful. For example, treatment of (1) or (2) with NaH or KH in ether or tetrahydrofuran solution readily gave the corresponding alkoxides, but the anion failed to attack the CCl_3 functionality even in the presence of 18-crown-6, or by use of the aprotic solvents DMF or HMPA, and the starting materials were recovered unchanged. Presumably expulsion of Cl^- requires electrophilic assistance, and this is provided by a polar protic solvent. Silver ion-assisted extrusion of Cl^- from the alcohols (1) or (2) likewise failed, indicating that the preliminary formation of the alkoxide is also essential to the reaction. Finally, direct synthesis of a dichloroepoxide by epoxidation of a 1,1-dichloroalk-1-ene was also attempted; 1,1-dichlorononon-1-ene was prepared by adapting literature procedures [17] but it failed to react, for example, with *m*-chloroperoxybenzoic acid or with peroxyacetic acid. Nevertheless, Scheme 5 is consistent with all of the available evidence, including the known stoicheiometry [3] of the reaction.

Reductive Dehalogenation of the Trichloromethyl Alcohols.—Reductive dehalogenation ($CCl_3 \longrightarrow CHCl_2 \longrightarrow CH_2Cl \longrightarrow CH_3$) would clearly be of synthetic interest, particularly if each of the reduction products could be prepared specifically by appropriate choice of the reducing agent.

The Cl_3C group proved to be completely inert to a number of 'dissolving metal' reductions (*e.g.* Zn–Et_2O–AcOH, Zn–EtOH) or problems arose from the alkoxide-initiated reactions described earlier (*e.g.* with Na–EtOH, or Li in THF–Bu^{t}OH). Protection of the OH group in (1) or (2) as the methoxyethoxymethyl (MEM) ether, however, simply increased the stability of the substrate and the Cl_3C group failed to react even with Na–EtOH or Na or Li in THF–Bu^{t}OH.

The ene adduct (2) reacted with a large excess of lithium aluminium hydride in ether (20 °C, 36 h) affording a 1 : 1 mixture of (29) and (30) in good yield. Similar reduction of (1) gave (31), (32), and (33) in 6 : 1 : 5 ratio. The product ratios highlight the relative reactivities of the mono-, di-, and trichlorinated compounds and indicate that reduction probably occurs by an S_N2 process whereby steric accessibility is more important than the effects of inductive electron withdrawal by chlorine. A more efficient reduction of (2) was achieved by use of a $LiAlH_4$–Bu^n_3SnCl mixture to generate Bu^n_3SnH *in situ*; [18] small quantities of azobisisobutyronitrile were employed as the radical initiator in benzene at reflux for 48 h. The conversion of (2) into (29) was almost quantitative, but removal of tin compounds in the work-up proved rather difficult. Monitoring the reaction revealed that chlorine removal became progressively more difficult, reflecting the diminution in radical stability in the sequence $R\dot{C}Cl_2 > R\dot{C}HCl > R\dot{C}H_2$. Reductions using sodium bis(2-methoxyethoxy)aluminium hydride (Red-al) were also effected; these were faster than with $LiAlH_4$ and the monochloro compounds accumulated to a greater extent. However, yields were lower because of decomposition and side reactions.

For comparison purposes the $LiAlH_4$ reduction of bromal–alkene ene adducts was also investigated. Reaction of (34) with excess $LiAlH_4$ led to the complete disappearance of starting material within 4 h. The fully reduced alcohol (37) [= (33)] and the partially reduced alcohols (35) and (36) were



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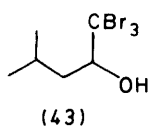

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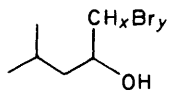
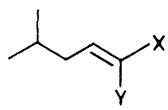


(44) $x = 1, y = 2$
(45) $x = 2, y = 1$
(46) $x = 3, y = 0$



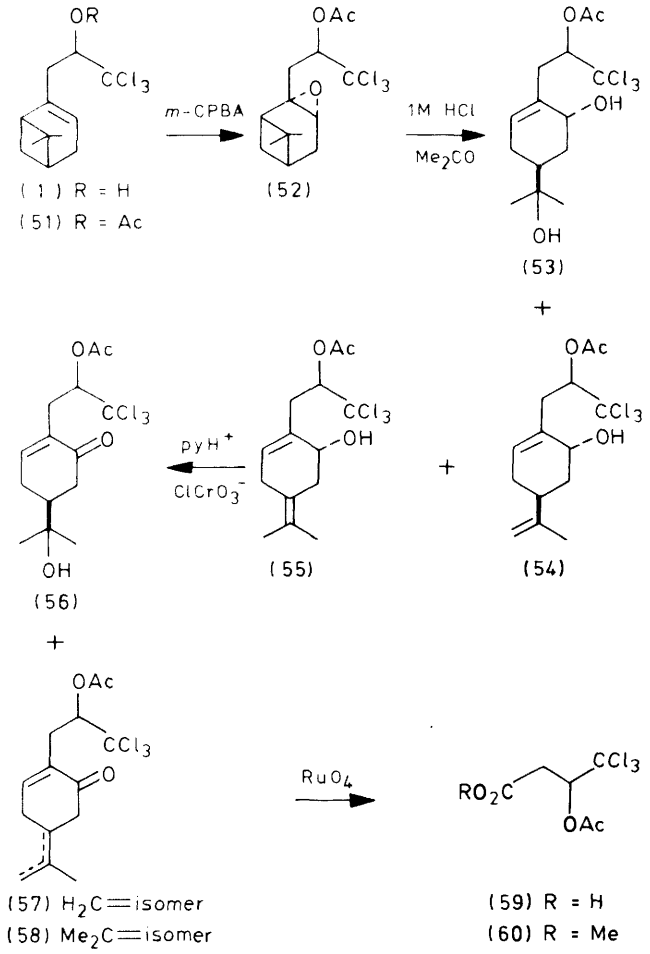
(47) X = Y = Br
(48) X = Br, Y = H
(49) X = H, Y = Br
(50) X = Y = H

isolated, but the bromo-alkenes (38)—(40) and alkene (41) were the principal constituents of the product mixture. In order to clarify this surprising result the hydrogenation product (43) of the isobutene–bromal ene adduct (42) was also reduced with $LiAlH_4$. The products, which distilled over a wide temperature range, were examined by various spectroscopic and chromatographic techniques. G.l.c./mass spectrometry of the lowest boiling fraction conclusively identified the bromoalkenes (37)—(49) in addition to the fully reduced alcohol (46). The higher boiling fractions were shown by ^1H n.m.r. to contain (44) and (45). The reaction was also believed to have produced (50), but its high volatility made successful isolation impossible. A reasonable explanation for the formation of bromoalkenes can be visualized by assuming a four-centred transition state with abstraction of Br^+, as proposed by Sydnes and Skattebøl [19] to account for the by-products formed on reaction of gem-dihalogenocyclopropanes with Red-al. Although the difference in behaviour between the tribromo- and trichloro-methyl alcohols can be attributed to the greater polarizability of bromine, we have nevertheless observed the formation of appreciable quantities of the chloroalkenes (38; X = Y = Cl), (39; X = Cl, Y = H), and (40; X = H, Y = Cl) in the $LiAlH_4$ reduction of (1) at higher temperatures (boiling di-n-butyl ether as solvent). The major product (63%) was the fully reduced alcohol (33).

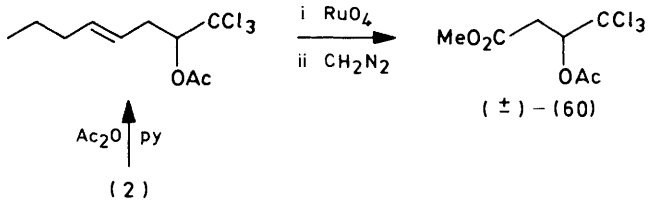
The above results are complementary to electrochemical reduction in which specific conversion of CCl_3 into $CHCl_2$ has been achieved.[20] However, dichloromethyl alcohols can be prepared directly by the Lewis acid catalysed ene addition of dichloroacetaldehyde to olefins.[21]

Asymmetric Synthesis by Cleavage of the (−)-β-*Pinene Ene Adducts.*—The highly selective asymmetric induction observed in the ene reactions of (−)-β-pinene with both chloral and bromal [4a,5] provides the possibility of developing chiral syntheses from adducts (1) and (34). Similar possibilities also exist for the ene adducts from (−)-β-pinene and glyoxylate and pyruvate esters, and fluoral which can also be obtained in high diastereoisomeric purity.[16]

Attempts to detach the chiral centre C-11 in (1) or (34) without destruction of the pinene skeleton failed. The C-10 position proved to be resistant to both allylic bromination and oxidation, and when reaction was observed it involved attack at the alternative allylic site or skeletal rearrangement of the pinene moiety. Ozonolytic cleavage suffered from poor reproducibility and product yields ranged from 0 to 35%. A successful oxidation–cleavage route is summarized in Scheme 7, and is a modification of the basic sequence employed by Spencer and Hill [22] to degrade the methyl pyruvate–β-pinene ene adduct. Pure 11(*S*)-(1) [5] was converted into the acetate



Scheme 7.



Scheme 8.

derivative (51) which was transformed according to Scheme 7 into (59) and a mixture of dicarboxylic acids. Treatment of this mixture with excess diazomethane followed by fractional distillation under reduced pressure afforded the acetoxy ester (60), $[\alpha]_D^{24}$ −27° (*c* 0.6240, $CHCl_3$) in 9% yield (not optimised) overall from (1). For comparison purposes (±)-(60) was also prepared, Scheme 8. Treatment of (±)-(60) in $CDCl_3$ with the chiral lanthanide shift reagent tris[3-(trifluoromethylhydroxymethylene)-(+)-camphorato]europium(III), Eu(tfc)$_3$, produced broadening of all the ^{1}H n.m.r. signals and splitting of the O·CO·CH_3 singlet into a fine doublet and the C*H*OAc resonance into an eight peak signal from the original doublet of doublets. No splitting or broadening of the ^{1}H n.m.r. resonances of (−)-(*S*)-(60) was observed under identical conditions with added Eu(tfc)$_3$. Additional proof that no significant racemization occurred in the use of Scheme 7 was provided by converting an 83 : 17 mixture [5] of 11-(*R*)-(1): 11-(*S*)-(1) into predominantly (+)-(*R*)-(60) by the same route; contamination by *ca.* 15—20% (−)-(*S*)-(60) was clearly visible in the Eu(tfc)$_3$ shifted ^{1}H n.m.r. spectrum.

Experimental

General details, instrumentation, and procedures for the preparation of starting materials, notably (1), (2), (21), (34), and (42), are to be found in the first paper of this series.[1]

1,1,1-*Trichloro-octan*-2-*ol* (4).—A mixture of 1,1,1-trichloro-oct-4-en-2-ol (2) (4.6 g, 20 mmol), ethyl acetate (50 ml), and PtO_2 (0.01 g) was shaken in an atmosphere of hydrogen at room temperature and pressure. Uptake of 20 mmol of hydrogen took place in *ca.* 10 min, but no further absorption was observed. Conventional work-up afforded a clear *colourless oil* (4.4 g, 96%), b.p. 81—82 °C/2 mmHg (Found: C, 40.6; H, 6.4. $C_8H_{15}Cl_3O$ requires C, 41.1; H, 6.4%); *m*/*z* 232 ($M^{+\cdot}$, absent) 178.0310 ($M^{+\cdot}$ − H_2O − HCl; C_8H_{12} $^{35}Cl_2$ requires 178.0316); n_D^{27} 1.4730; $\nu_{max.}$ (film) 3 430, 2 900, 1 470, 1 085, and 800 cm^{-1}; δ 4.04 (1 H, m, reduced on D_2O shake to dd, separations 2 and 10 Hz, $CHCCl_3$), 3.00 (1 H, d, *J* 6 Hz, absent on D_2O shake, OH), 2.0 [1 H, complex m, n-C_5H_{11}-C*H*(H)], 1.8—1.4 [3 H, complex m, n-$C_4H_9CH_2CH(H)$], 1.3 (6 H, m, Me(CH_2)$_3$), and 0.90 (3 H, t, *J* 7 Hz, CH_3).

1,1,1-*Trichloro-octan*-2-*one* (5).—To a mixture of chromium trioxide (1.25 g, 12.5 mmol), glacial acetic acid (50 ml), and concentrated sulphuric acid (20 ml) was added the alcohol (4) (2.3 g, 10 mmol) in acetic acid (30 ml); stirring was continued for a further 4 h at room temperature. The solution was diluted to 400 ml with water and extracted with dichloromethane (4 × 50 ml). The organic extracts were washed with saturated aqueous sodium hydrogen carbonate (4 × 50 ml) and water (50 ml), dried (Na_2SO_4). Filtration and removal of solvent under reduced pressure afforded the crude ketone (2.1 g, 92%) as a pale yellow oil with a heavy sweet odour. Distillation, 67.5—69 °C/5 mmHg, gave a clear colourless oil (1.6 g, 73%); *m*/*z* 230 ($M^{+\cdot}$, absent), 113 (C_6H_{13}-$CO^{+\cdot}$), 85 ($C_6H_{13}^{+\cdot}$); n_D^{24} 1.4596; $\nu_{max.}$ (film) 2 900, 1 745, and 820 cm^{-1}; δ 2.98 (2 H, t, *J* 8 Hz, CH_2CO), 1.75 (2 H, br m, CH_2CH_2CO), 1.35 [6 H, br m, $CH_3(CH_2)_3$], and 0.90 (3 H, t, *J* 7 Hz, CH_3).

Heptanoic Acid (6) *from Ketone* (5).—A solution of the ketone (5) (2.8 g, 12 mmol) and sodium hydroxide (5 g, 125 mmol) in water (50 ml) was heated on a steam-bath for 2 h with occasional swirling. The cooled solution was extracted with chloroform (3 × 25 ml), and the aqueous layer then acidified with concentrated hydrochloric acid and extracted with chloroform. These extracts were washed with water (25 ml) and dried (Na_2SO_4). Filtration and removal of solvent under reduced pressure gave the crude acid as a brown oil (1.3 g, 81%). Distillation, 117—120 °C/15 mmHg, afforded colourless material (1.1 g, 69%), identical in all respects to authentic heptanoic acid.

1,1,1-*Trichloro-oct*-4-*en*-2-*yl Toluene*-p-*sulphonate* (7).—The tosyl ester was prepared in a fashion similar to that used in the preparation of (1)-tosylate.[4b] The crude ester (*ca.* 100%) was obtained as a dark brown oil; ^{1}H n.m.r. assay indicated the presence of toluene-*p*-sulphonic acid (*ca.* 10%). Purification proved unsuccessful, and the impure ester was employed in the preparation of ethyl octa-2,4-dienoate (9).

Ethyl Octa-2,4-*dienoate* (9).—A solution of crude tosyl ester (7) (3.9 g, *ca.* 9 mmol) in dry ethanol (25 ml) was run into

sodium ethoxide solution [prepared from sodium (1.2 g, 10 mmol) and dry ethanol (100 ml)] under nitrogen. The mixture was stirred at room temperature for 24 h, the bulk of the solvent then removed under reduced pressure, and the residue taken up in water (200 ml). The ether extracts (3 × 50 ml) of the aqueous suspension were washed with water and dried (Na_2SO_4). Filtration and removal of the solvent under reduced pressure afforded a brown oil (2.0 g, 131%) which was purified by pressure column chromatography (benzene) to give a colourless sweet-smelling oil (0.8 g, 53%); *m/z* 168.1141 ($C_{10}H_{16}O_2^{+\cdot}$ requires 168.1150), 125 ($M^{+\cdot} - C_3H_7$), 123 ($M^{+\cdot}$ − OEt), and 95 ($M^{+\cdot} - CO_2Et$); $\nu_{max.}$ (film) 2 950, 1 710, 1 640, 1 600, 1 180, and 970 cm^{-1}; δ 7.42 (1 H, complex m, C-4 olefinic H), 6.60 (1 H, t, *J* 11 Hz, C-3 olefinic H), 6.10 (1 H, dt, separations 7 and 16 Hz, C-5 olefinic H), 5.60 (1 H, d, *J* 11 Hz, C-2 olefinic H), 4.24 (2 H, q, *J* 7 Hz, OCH_2), 2.20 (2 H, q, *J* 7 Hz, CH_2CH=), 1.50 (2 H, m, CH_2CH_3), 1.28 (3 H, t, *J* 7 Hz, ester CH_3), and 0.93 (3 H, t, *J* 7 Hz, CH_3); $\lambda_{max.}$ (EtOH) 262 nm (log ε 4.35).

2-*Methoxyoct*-4-*enoic Acid* (11).—Potassium hydroxide pellets (7.0 g, 126 mmol) were dissolved in hot methanol (150 ml) and a solution of 1,1,1-trichloro-oct-4-en-2-ol (2) (4.64 g, 20 mmol) in methanol (30 ml) was added dropwise with stirring. The solution was then heated under reflux for 3 h, during which time an orange colouration developed and potassium chloride was precipitated. After the mixture had cooled, the excess methanol was removed under reduced pressure and the residue treated with water (150 ml). The aqueous solution was extracted with CH_2Cl_2 (2 × 50 ml) and then acidified to pH 1 by the cautious dropwise addition of concentrated hydrochloric acid. The acidic organic products were then extracted into CH_2Cl_2 (3 × 50 ml) and the organic solution washed with water (20 ml) and dried ($MgSO_4$). Filtration and removal of the solvent under reduced pressure afforded an oil which was distilled under reduced pressure to give the *acid* (2.7 g, 78%), b.p. 80—81 °C/0.01 mmHg, as a colourless liquid, n_D^{21} 1.4490; *m/z* 172.1092 ($C_9H_{16}O_3^{+\cdot}$ requires 172.1099); $\nu_{max.}$ (film) 3 600—2 400, 2 960, 2 920, 1 720, 1 120, and 975 cm^{-1}; δ 10.70 (1 H, br s, absent on D_2O shake, OH), 5.48 (1 H, highly perturbed dd, A of AB type, separations 5.5 and 14 Hz, =C*H*CH_2CHOMe), 5.30 (1 H, highly perturbed dd, B of AB type, separations 5.5 and 14 Hz, CH_2CH_2CH=C*H*), 3.80 (1 H, t, separation 6 Hz, C*H*OMe), 3.42 (3 H, s, OCH_3), 2.48 (2 H, t, separation 6 Hz, CH_2CHOMe), 1.96 (2 H, q, separation 6 Hz, CH_2CH_2CH=), 1.35 (2 H, sextet, separation 7 Hz, CH_2Me), and 0.87 (3 H, t, *J* 7 Hz, CH_3).

The CH_2Cl_2 washings taken prior to acidification of the aqueous solution contained no significant organic products.

Methyl Hept-3-*enoate* (13).—To a solution of di-isopropylamine (0.734 g, 7.27 mmol) in $LiAlH_4$-dried THF (10 ml), cooled to −5 °C and under N_2, was added dropwise with stirring a solution of n-butyl lithium in hexane (0.465 g, 7.27 mmol BuLi; *i.e.* 4.38 ml of 1.66M-solution). The lithium di-isopropylamide (LDA) solution which was formed was stirred for 15 min at −5 °C and 2-methoxyoct-4-enoic acid (11) (0.5 g, 2.9 mmol) dissolved in THF (5 ml) was then added dropwise with stirring whilst the mixture was maintained at −5 °C; an intense orange colouration developed. After a further 1.5 h at −5 °C, the solution was cooled to −78 °C and then a rapid stream of O_2 gas was passed through the liquor; the colour faded to pale yellow and the viscosity increased. The reaction mixture was maintained at −78 °C while a solution of (+)-camphor-10-sulphonic acid (2.03 g, 8.14 mmol) in THF (10 ml) was added dropwise. The solution was then allowed to warm up to room temperature and stirring continued for a further 2 h prior to treatment with saturated brine (100 ml) and extraction with ether (2 × 60 ml). The organic solution was washed with 10% aqueous sodium sulphite (30 ml) and brine (30 ml) and dried ($MgSO_4$). Filtration and solvent removal under reduced pressure yielded the crude product as a light brown liquid which was chromatographed on a short pressure column (CH_2Cl_2) to afford the *ester* as a colourless liquid (0.1 g, 25%) after Kugelröhr distillation, 72 °C/15 mmHg (lit.,[23] b.p. 78—79 °C/25 mmHg); $\nu_{max.}$ (film) 2 950, 1 740, 1 165, and 975 cm^{-1}; δ 5.57 (2 H, m, olefinic H), 3.70 (3 H, s, OCH_3), 3.07 (2 H, m, CH_2CO_2), 2.03 (2 H, m, CH_2CH=), 1.41 (2 H, sextet, separation 7 Hz, CH_2Me), and 0.89 (3 H, t, *J* 7 Hz, CH_3).

2-*Methoxy*-3-{(1S,5S)-6,6-*dimethylbicyclo*[3.1.1]*hept*-2-*en*-2-*yl*}*propanoic Acid* (10).—(*a*) The procedure was the same as for the preparation of (11) using the KOH–MeOH method. Thus, the (−)-β-pinene–chloral adduct (1) from the $AlCl_3$-catalysed ene reaction (2.83 g, 10 mmol) was refluxed with a solution of potassium hydroxide (3.5 g, 63 mmol) in methanol (100 ml) for 3 h. Work-up, as above, afforded a pale yellow oil which on Kugelröhr distillation at 105 °C/0.1 mmHg afforded the *methoxy acid* (1.7 g, 76%) (Found: C, 69.25; H, 9.38. $C_{13}H_{20}O_3$ requires C, 69.61; H, 9.38%); $[\alpha]_D^{24}$ −5.5°; $\nu_{max.}$ (film) 3600—2 400, 2 970, 2 900, 1 720, and 1 120 cm^{-1}; δ * 10.40 (1 H, br s, absent on D_2O shake, OH), 5.41 (1 H, m, 3-H), 3.86 (1 H, t, separation, 6.5 Hz, 11-H), 3.45 (3 H, s, OCH_3), 2.54—2.40 (3 H, complex m, 7β-H + 2 × 10-H), 2.36—2.20 (2 H, complex m, 4-H), 2.20—2.00 (2 H, complex m, 1-H + 5-H), 1.30 (3 H, s, 3 × 8-H), 1.18 (1 H, d, *J* 8 Hz, 7α-H), and 0.87 (3 H, s, 3 × 9-H).

The first set of CH_2Cl_2 extracts contained virtually no neutral organic material.

(*b*) To a solution of sodium methoxide prepared from sodium (0.6 g, 26 mmol) and dry methanol (25 ml) was added dropwise and with stirring a solution of ene adduct (1) of the same origin as in (*a*) (1.15 g, 4.1 mmol) in dry methanol (5 ml). The solution was stirred at room temperature for 24 h and the development of a yellow colouration was accompanied by precipitation of sodium chloride. The excess methanol was removed under reduced pressure and the residue was then diluted with water (60 ml) and extracted with CH_2Cl_2 (3 × 25 ml). Following acidification of the aqueous solution to pH 1 using concentrated hydrochloric acid, further CH_2Cl_2 extracts (3 × 25 ml) were taken. The two sets of organic extracts were washed separately with water (15 ml) and each solution was dried (Na_2SO_4), then filtered, and the solvent removed under reduced pressure. The first set of extracts yielded a trace of unchanged starting material while the second set, taken after acidification of the aqueous solution, afforded (0.7 g, 77%) the methoxy acid which was purified by Kugelröhr distillation at 110—111 °C/0.02 mmHg, $[\alpha]_D^{24}$ −7.2°. The product had spectroscopic properties identical with the material prepared by method (*a*).

Methyl 2-{(1S,5S)-6,6-*Dimethylbicyclo*[3.1.1]*hept*-2-*en*-2-*yl*}*ethanoate* (12).—The procedure was the same as for the preparation of methyl hept-3-enoate (13), and utilised the methoxy acid (10) (0.65 g, 2.9 mmol); other reagent quantities and reaction times were identical. The reaction residue after chromatography on a short pressure column afforded the *product* (0.225 g, 40%), as a colourless liquid on Kugelröhr distillation at 48 °C/0.05 mmHg (lit.,[24] b.p. 42—44 °C/0.3 mmHg); $\nu_{max.}$ (film) 3 050, 2 990, 2 950, 2 840, 1 740, 1 655, and 1 165 cm^{-1}; δ 5.42 (1 H, m, 3-H), 3.76 (3 H, s, OCH_3), 3.00 (2 H, br s, 2 × 10-H), 2.42 (1 H, m, 7β-H), 2.32—2.20 (2 H,

* IUPAC numbering of ring; C-10 is the attached atom of the side chain.

complex m, 2 × 4-H), 2.18—2.02 (2 H, complex m, 1-H and 5-H), 1.27 (3 H, s, 3 × 8-H), 1.10 (1 H, d, *J* 9 Hz, 7α-H), and 0.83 (3 H, s, 3 × 9-H).

Methyl 2-Methoxy-3-{(1S,5S)-6,6-dimethylbicyclo[3.1.1]hept-2-en-2-yl}propanoate (15).—(*a*) The procedure was the same as detailed for the preparation of the methoxy acid (10) by route (*b*) up to the completion of the reaction at room temperature, except that stirring was continued for 48 h. The starting material (1) originated from the $AlCl_3$-catalysed addition of chloral to (−)-β-pinene (1.15 g, 41 mmol) and comprised at 76 : 24 mixture of the 11(*S*)- and 11(*R*)-diastereoisomers.[4,5] The methanolic solution was acidified to pH 1 by the cautious dropwise addition of the minimum of concentrated hydrochloric acid. The bulk of the methanol and water was rapidly removed on a rotary evaporator and the residue diluted with 1M-sodium hydroxide solution (75 ml). The aqueous alkaline solution contained globules of organic material which were extracted into CH_2Cl_2 (3 × 25 ml). The aqueous solution was acidified to pH 1 with concentrated hydrochloric acid and re-extracted with CH_2Cl_2 (3 × 25 ml). Each organic solution was washed with water (10 ml), dried (Na_2SO_4), filtered, and the solvent removed under reduced pressure. The first set of extracts containing the neutral organic material afforded the *methoxy ester* (0.8 g, 83%) which was purified by pressure column chromatography ($CHCl_3$) and then Kugelröhr distillation at 58—60 °C/0.1 mmHg (Found: C, 70.4; H, 9.3. $C_{14}H_{22}O_3$ requires C, 70.56; H, 9.30%); $[\alpha]_D^{24}$ −8°; $\nu_{max.}$ (film) 3 040, 2 990, 2 930, 2 840, 1 750, 1 200, and 1 125 cm^{-1}; δ 5.38 (1 H, m, 3-H), 3.83 (1 H, t, separation 7 Hz, 11-H), 3.79 (3 H, s, CO_2CH_3), 3.40 (3 H, s, $CHOCH_3$), 2.50—2.30 (3 H, complex m, 2 × 10-H + 7β-H), 2.32—2.20 (2 H, complex m, 2 × 4-H), 2.16—2.00 (2 H, complex m, 1-H + 5-H), 1.30 (3 H, s, 3 × 8-H), 1.16 (1 H, d, *J* 8 Hz, 7α-H), and 0.84 (3 H, s, 3 × 9-H). Addition of small portions of the lanthanide shift reagent $Eu(fod)_3$ to the ^1H n.m.r. solution resolved some of the resonances due to the two diastereoisomers present: separate pairs of peaks were observed for the 3-H, 11-H, CO_2CH_3 and $CHOCH_3$ protons, and integration revealed a 75 : 25 ratio of 11(*S*) : 11(*R*) diastereoisomers [absolute stereochemistry is defined by the method (*c*) of synthesis of ester (15), below].

The second set of CH_2Cl_2 extracts, taken after the final acidification, afforded the methoxy acid (10) (0.06 g, 6.6%), $[\alpha]_D^{24}$ −7.2°.

(*b*) The experiment was repeated on the same scale using a sample of ene adduct (1) which originated from the thermal ene addition of chloral to (−)-β-pinene of 17 : 83 ratio of the 11(*S*) : 11(*R*) diastereoisomers. Treatment with sodium methoxide at room temperature for 44 h afforded the methoxy ester (15) (0.78 g, 81%), $[\alpha]_D^{24}$ −41°; ^1H n.m.r. analysis indicated a 17 : 83 ratio of 11(*S*) : 11(*R*) diastereoisomers. A small quantity (*ca.* 0.05 g, 5.5%) of the methoxy acid (10) was also isolated, $[\alpha]_D^{24}$ −36°.

(*c*) A sample of methyl 2-hydroxy-3-{(1*S*,5*S*)-6,6-dimethylbicyclo[3.1.1]hept-2-en-2-yl}propanoate (16) was provided by Kirollos,[16] and had been prepared from the $AlCl_3$-catalysed ene addition of methyl glyoxylate to (−)-β-pinene. The adduct (16) was known to be predominantly (85—90%) the 11(*R*)-diastereoisomer.

The hydroxy ester (16) (0.5 g, 2.25 mmol) was dissolved in methyl iodide (1.28 g, 9 mmol) and freshly prepared silver(I) oxide (0.783 g, 3.38 mmol) was added in small portions. The dark brown slurry was stirred magnetically and heated to promote gentle boiling of the methyl iodide. After 5 h the mixture was allowed to cool and ether (10 ml) was added. The silver(I) oxide was removed by suction filtration and washed thoroughly with ether (20 ml); the solvent from the colourless filtrate was removed under reduced pressure to afford essentially pure methoxy ester (15) (0.52 g, 98%); Kugelröhr distillation at 70 °C/0.2 mmHg; $[\alpha]_D^{24}$ −42°. The product was spectroscopically identical with material prepared by routes (*a*) and (*b*). Lanthanide shift studies [$Eu(fod)_3$] and comparison of specific rotations with the above samples established that overall retention of stereochemistry had occurred in the conversion of (1) into (15) by methanolic methoxide.

Cyclohex-1-enecarbaldehyde (23) *and 2-(Cyclohex-2-enyl)-2-hydroxyethanoic Acid* (22) *from the Hydrolysis of Ene Adduct* (21).—To a solution of sodium carbonate (0.6 g, 5.7 mmol) in water (12 ml) was added diastereoisomerically pure (21), (*R*,*R* + *S*,*S*)-2,2,2-trichloro-1-(cyclohex-2-enyl)ethanol (0.5 g, 2.2 mmol). The mixture was boiled under reflux for 75 min, allowed to cool to room temperature, and extracted with ether (2 × 15 ml). The aqueous solution was acidified to pH 1 with concentrated hydrochloric acid and re-extracted with ether (2 × 15 ml). The two sets of organic extracts were separately washed with water (10 ml), dried (Na_2SO_4), filtered, and the solvent removed under reduced pressure.

The first set of extracts, the neutral fraction, was a pale yellow liquid (0.09 g, 38%) which possessed the odour of almonds, and was identified as cyclohex-1-enecarbaldehyde (23); $\nu_{max.}$ (film) 3 030, 2 930, 2 850, 2 710, 1 685 and 1 635 cm^{-1}; δ 9.45 (1 H, s, CHO), 6.83 (1 H, m, olefinic H), 2.50—2.10 (4 H, complex m, allylic H), and 1.80—1.60 (4 H, complex m, 2 × CH_2).

The second set of extracts, the acidic fraction, afforded a viscous yellow oil which, after Kugelröhr distillation at 75 °C/0.1 mmHg, solidified with time; recrystallisation from chloroform afforded 2-(cyclohex-2-enyl)-2-hydroxyethanoic acid (22) (0.085 g, 25%) as a colourless solid, m.p. 126—127 °C; $\nu_{max.}$ (KBr) 3 700—2 400, 3 030, 2 950, 2 880, and 1 700 cm^{-1}; δ($[^2H_6]$acetone) 6.40 (2 H, br s, absent on D_2O shake, 2 × OH), 5.64—5.28 (2 H, m, olefinic H), 3.97 (1 H, d, *J* 4.5 Hz, *CH*OH), 2.50 (1 H, m, *CH*CHOH), 2.10—1.50 (6 H, complex m, 3 × CH_2); δ_C ($[^2H_6]$acetone) 206.21 (s, CO), 129.64 (d, CH=), 128.94 (d, CH=), 74.10 (d, CHOH), 40.78 (d, *C*HCHOH), 25.58 (t, CH_2), 23.94 (t, CH_2), and 22.20 (t, CH_2).

Repetition of the experiment using sodium hydroxide (0.5 g, 12.5 mmol) in place of sodium carbonate afforded both (22) and (23) in essentially identical yields.

Corollary Experiment; the Hydrolyses of Ene Adducts (1) *and* (2).—The hex-1-ene and (−)-β-pinene–chloral adducts (2) and (1), respectively, were treated with sodium carbonate solution as above. After a short reaction time (*ca.* 2 h) much starting material was recovered, whereas longer reaction times (*ca.* 6 h) gave complex mixtures of unidentified aldehydes carboxylic acids, and lactones in low yield.

E-2-*Hydroxyoct-4-enoic Acid* (27) *from the Phase-transfer Hydrolysis of Ene Adduct* (2).—The hex-1-ene–chloral adduct (2) (0.92 g, 4 mmol) was dissolved in dichloromethane (6 ml) and benzyltriethylammonium chloride (TEBAC) (0.05 g) was added. A solution of sodium hydroxide (4.8 g, 120 mmol) in water (9.6 ml) was then mixed with the organic solution and the two-phase system was subjected to vigorous mechanical shaking for a period of 6 h. The mixture was diluted with water and extracted with ether (25 ml). The organic solution contained no aldehyde products. The aqueous solution was then acidified to pH 1 by addition of concentrated hydrochloric acid and re-extracted with ether (2 × 25 ml). After washing with water (10 ml) the ether extracts were dried ($MgSO_4$), filtered, and the solvent removed under reduced pressure to afford *E*-2-hydroxyoct-4-enoic acid (27) (0.27 g, 35%); $\nu_{max.}$

(film) 3 600—2 400, 2 950, 1 720, 1 100 and 970 cm^{-1}; δ 7.30 (2 H, br s, absent on D_2O shake, 2 × OH), 5.48 (2 H, m, olefinic H), 4.26 (1 H, t, separation 6 Hz, C*H*OH), 2.48 (2 H, m, CH_2CHOH), 1.94 (2 H, q, *J* 7 Hz, CH_2CH_2CH=), 1.43 (2 H, sextet, separation 7 Hz, CH_3CH_2), and 0.87 (3 H, t, *J* 7 Hz, CH_3).

Conversely, reaction of (2) (0.92 g, 4 mmol) with an ice-cold solution of potassium hydroxide (1.0 g, 17.9 mmol) in water (10 ml) with stirring for 12 d at 0 °C, followed by work-up as above, afforded only *ca.* 5% of impure (27).

2-Hydroxy-3-{(1S,5S)-6,6-dimethylbicyclo[3.1.1]hept-2-en-2-yl}propanoic Acid (26) *from the Phase-transfer Hydrolysis of Ene Adduct* (1).—Using the same procedure as in the previous experiment the (−)-β-pinene–chloral ene adduct from an $AlCl_3$-catalysed reaction [diastereoisomer ratio 11(*S*) : 11(*R*) = 76 : 24][4,5] (1.13 g, 4 mmol) was shaken with 50% aqueous sodium hydroxide in the presence of TEBAC for 6.5 h. Work-up afforded 0.33 g, (39%) of the hydroxy acid (26) as a viscous liquid; $\nu_{max.}$ (film) 3 600—2 400, 3 020, 2 910, 1 720, and 1 095 cm^{-1}; δ 6.55 (2 H, br s, absent on D_2O shake, 2 × OH), 5.49 (1 H, m, 3-H), 4.34 (1 H, dd, separations 4.5 and 8 Hz, 1-H), 2.53—2.35 (3 H, complex m, 2 × 10-H and 7β-H), 2.35—2.20 (2 H, complex m, 2 × 4-H), 2.20—2.00 (2 H, m, 1-H and 5-H), 1.30 (3 H, s, 3 × 8-H), 1.20 (1 H, d, *J* 8 Hz, 7α-H) and 0.86 (3 H, s, 3 × 9-H).

Methyl 2-Hydroxy-3-{(1S,5S)-6,6-dimethylbicyclo[3.1.1]hept-2-en-2-yl}propanoate (16) *from Hydroxy Acid* (26).—The crude hydroxy acid (26) from the previous experiment (0.2 g, 0.95 mmol) dissolved in ether (2 ml) was treated with an excess of a freshly prepared ice-cold solution of diazomethane in ether. Unchanged diazomethane and the ether was allowed to evaporate overnight, and the crude product then chromatographed in a pressure column (CH_2Cl_2) to afford 0.19 g (89%) of the pure hydroxy ester (16). G.l.c. analysis on a 50 m Carbowax 20M column revealed that the ratio of diastereoisomers 11(*S*) : 11(*R*) was 77 : 23, with respective retention times of 77 and 78 min; the relationship between absolute stereochemistry and retention time is based upon the work of Kirollos.[16] This result confirms retention of configuration during the aqueous base hydrolysis of (1). Physical data: $\nu_{max.}$ (film) 3 470, 2 980, 2 920, 2 840, 1 740, 1 220, and 1 100 cm^{-1}; δ 5.42 (1 H, m, 3-H), 4.28 (1 H, dd, separations 5 and 7 Hz, 11-H), 3.80 (3 H, s, CO_2CH_3), 2.60 (1 H, br s, absent on D_2O shake, OH), 2.50—2.30 (3 H, complex m, 2 × 10-H and 7β-H), 2.26 (2 H, m, 2 × 4-H), 2.16—1.98 (2 H, m, 1-H and 5-H), 1.29 (3 H, s, 3 × 8-H), 1.17 (1 H, d, *J* 9 Hz, 7α-H), and 0.85 (3 H, s, 3 × 9-H).

Reduction of 1,1,1-Trichloro-3-{(1S,5S)-6,6-dimethylbicyclo[3.1.1]hept-2-en-2-yl}propan-2-ol (1) *with* $LiAlH_4$: *Formation of Compounds* (31), (32), (33), (38; X=Y=Cl), (39; X=Cl, Y=H), (40; X=H, Y=Cl) *and* (41).—(*a*) To a suspension of $LiAlH_4$ (0.8 g, 21.1 mmol) in dry ether (25 ml) was added dropwise and with stirring a solution of the ene adduct (1), from an $AlCl_3$-catalysed reaction [11(*S*) : 11(*R*) = 76 : 24][4,5] (2.0 g, 7 mmol) in ether (15 ml), at a rate such that a gentle reflux was maintained. The mixture was stirred at room temperature for 48 h, then quenched with water (10 ml). The white inorganic precipitate was dissolved by addition of 2M-hydrochloric acid (15 ml) and the organic layer then separated. The aqueous solution was extracted with ether (25 ml) and the combined organic solutions then washed with water (10 ml) and dried ($MgSO_4$). Filtration and solvent removal under reduced pressure afforded a mixture of three products: 1,1-*dichloro*-3-{(1S,5S)-6,6-*dimethylbicyclo*[3.1.1]*hept*-2-*en*-2-*yl*}*propan*-2-*ol* (31), 1-*chloro*-3-{1S,5S)-6,6-*dimethylbicyclo*[3.1.1]*hept*-2-*en*-2-*yl*}*propan*-2-*ol* (32), and 3-{1S,5S)-6,6-*dimethylbicyclo*[3.1.1]*hept*-2-*en*-2-*yl*}*propan*-2-*ol* (33) in a ratio 6 : 1 : 5 (yield *ca.* 90%). Separation of these products was achieved by chromatography on a pressure column (CH_2Cl_2).

Compound (31) was purified by Kugelröhr distillation at 86 °C/0.1 mmHg (Found: C, 57.8; H, 7.3. $C_{12}H_{18}Cl_2O$ requires C, 57.84; H, 7.28%), $[\alpha]_D^{24}$ −32.2°, ratio of diastereoisomers (from ^{13}C n.m.r. analysis) was 76 (11*S*) : 24(11*R*). This compound was spectroscopically identical with the ene adduct obtained from (−)-β-pinene and dichloroacetaldehyde:[21] $\nu_{max.}$ (film) 3 400, 3 020, 2 900, 1 090, 790, and 755 cm^{-1}; δ 5.75 (*ca.* 0.25 H, d, separation 4 Hz, 12-H of 11(*R*)-isomer), 5.74 (*ca.* 0.75 H, d, separation, 4 Hz, 12-H of 11(*S*)-isomer), 5.44 (1 H, m, 3-H), 3.92 (1 H, m, reduced complexity on D_2O shake, 11-H), 2.45—2.20 (6 H, complex m, reduced to 5 H on D_2O shake, 2 × H-10 + 2 × 4-H + 7β-H + OH), 2.16—2.00 (2 H, m, 1-H + 5-H), 1.29 (3 H, s, 3 × 8-H), 1.13 (1 H, d, *J* 8 Hz, 7α-H), 0.87 (3 H, m, 3 × 9-H); δ_C for 11(*S*)-diastereoisomer 143.15 (s, C-2), 121.04 (d, C-3), 76.20 (d, C-12), 74.00 (d, C-11), 45.94 (d, C-1), 40.70 (d, C-5), 40.08 (t, C-10), 37.93 (s, C-6), 31.79 (t, C-4), 31.46 (t, C-7), 26.23 (q, C-8) and 21.20 (q, C-9); 11(*R*)-diastereoisomer 143.45 (s, C-2), 121.33 (d, C-3), 76.10 (d, C-12), 73.94 (d, C-11), 45.77 (d, C-1), 40.70 (d, C-5), 40.08 (t, C-10), 38.05 (s, C-6), 31.90 (t, C-4), 31.46 (t, C-7), 26.23 (q, C-8), and 21.14 (q, C-9).

Compound (32) was spectroscopically identical with the ene adduct obtained from (−)-β-pinene and chloroacetaldehyde:[21] $\nu_{max.}$ (film) 3 400, 2 920, and 1 060 cm^{-1}; δ 5.42 (1 H, m, 3-H), 3.86 (1 H, m, 11-H), 3.75—3.40 (2 H, m, AB of ABX, 2 × 12-H), 2.60—2.05 (8 H, complex m, reduced to 7 H on D_2O shake, 2 × 10-H + 2 × 4-H + 7β-H + 1-H + 5-H + OH), 1.30 (3 H, s, 3 × 8-H), 1.21 (1 H, d, *J* 8 Hz, 7α-H), and 0.87 (3 H, s, 3 × 9-H).

Compound (33) was purified by Kugelröhr distillation at 60 °C/0.03 mmHg, *m/z* 180.1526 ($C_{12}H_{20}O^{+\cdot}$ requires 180.1514); $\nu_{max.}$ (film) 3 360, 3 030, 2 930, 2 840, and 1 080 cm^{-1}; δ 5.40 (1 H, m, 3-H), 3.82 (1 H, sextet, separation 6 Hz, 11-H), 2.52—2.10 (7 H, complex m, 2 × 10-H + 2 × 4-H + 7β-H + 1-H + 5-H), 1.94 (1 H, br s, absent on D_2O shake, OH), 1.30 (3 H, s, 3 × 8-H), 1.19 (4 H, d, *J* 7 Hz, 3 × 12-H and 7α-H) and 0.87 (3 H, s, 3 × 9-H).

(*b*) To a suspension of $LiAlH_4$ (0.76 g, 20 mmol) in sodium-dried di-n-butyl ether (15 ml) was added dropwise and with stirring a solution of (1) (1.0 g, 3.53 mmol) in di-n-butyl ether (5 ml). The mixture was heated at 100 °C for 15 h then, after cooling, the reaction was quenched and worked-up as for (*a*). The crude product, a complex mixture of compounds, was chromatographed in a pressure column (CH_2Cl_2) and the fully reduced alcohol (33) (0.4 g, 63%) was isolated together with small quantities of (31) and (32). An additional 0.16 g of a mixture of several compounds was obtained from the column; from capillary column g.l.c. retention characteristics and spectroscopic data were identified (1*S*,5*S*)-6,6-dimethyl-2-(prop-2-enyl)bicyclo[3.1.1]hept-2-ene (41) and *E*- and *Z*-(1*S*,5*S*)-6,6-dimethyl-2-(3-chloroprop-2-enyl)bicyclo[3.1.1]-hept-2-ene (39; X=Cl, Y=H) and (40; X=H, Y=Cl). The dichlorinated compound (1*S*,5*S*)-6,6-dimethyl-2-(3,3-dichloroprop-2-enyl)bicyclo[3.3.1]hept-2-ene (38; X=Y=Cl) was also believed to be present.

Reduction of Chloral Ene Adducts (1) *and* (2) *with Red-al.*—Toluene solutions of the ene adducts (1) and (2) were separately treated with an excess of a 70% (w/w) solution of sodium bis(2-methoxyethoxy)aluminium hydride (Red-al) in benzene and stirred at room temperature or under reflux for varying time periods (5—24 h). After quenching with 2M-hydrochloric acid, work-up afforded mixtures of mono-

and di-chlorinated products, together with very small quantities of the fully dehalogenated alcohols.

Reduction of 1,1,1-*Tribromo*-3-{(1S,5S)-6,6-*dimethylbicyclo*[3.1.1]*hept*-2-*en*-2-*yl*}*propan*-2-*ol* (34) *with* $LiAlH_4$: *Formation of Compounds* (35)—(41).—To a stirred suspension of $LiAlH_4$ (0.7 g, 18.5 mmol) in dry ether (30 ml) was added dropwise, over a period of 15 min, a solution of the ene adduct (34) (2.09 g, 5.0 mmol) in ether (15 ml). The mixture was stirred at room temperature for 4 h and then quenched and worked up using the same procedure as for the $LiAlH_4$ reduction of (1). The crude product was a complex mixture of alcohols and alkenes, with most of the compounds containing one or more bromine atoms. Chromatography in a pressure column enabled the isolation of pure samples of 1,1-*dibromo*-3-{(1S,5S)-6,6-*dimethylbicyclo*[3.1.1]*hept*-2-*en*-2-*yl*}*propan*-2-*ol* (35), 1-*bromo*-3-{(1S,5S)-6,6-*dimethylbicyclo*-[3.1.1]*hept*-2-*en*-2-*yl*}*propan*-2-*ol* (36), and 1-{(1S,5S)-6,6-*dimethylbicyclo*[3.1.1]*hept*-2-*en*-2-*yl*}*propan*-2-*ol* (37). The alkene products (*ca.* 0.75 g) were believed to be (1*S*,5*S*)-6,6-dimethyl-2-(prop-2-enyl)bicyclo[3.1.1]hept-2-ene (41), *E*- and *Z*-(1*S*,5*S*)-6,6-dimethyl-2-(3-bromoprop-2-enyl)bicyclo[3.1.1]-hept-2-ene (39) and (40), and (1*S*,5*S*)-6,6-dimethyl-2-(3,3-dibromoprop-2-enyl)bicyclo[3.1.1]hept-2-ene (38), but these compounds were not individually isolated.

Compound (35): 0.23 g (13.6%); $\nu_{max.}$ (film) 3 430, 2 950, 2 840, 1 080, and 750 cm^{-1}; δ 5.75 (1 H, d, *J* 3 Hz, 12-H), 5.42 (1 H, m, 3-H), 3.92 (1 H, m, reduced complexity on D_2O shake, 11-H), 2.60—2.20 (6 H, complex m, reduced to 5 H on D_2O shake, 2 × 10-H + 2 × 4-H + 7β-H + OH), 2.18—2.00 (2 H, m, 1-H and 5-H), 1.29 (3 H, s, 3 × 8-H), 1.13 (1 H, d, *J* 8 Hz, 7α-H), and 0.87 (3 H, m, 3 × 9-H).

Compound (36): trace; $\nu_{max.}$ (film) 3 420, 2 940, 2 840, and 1 080 cm^{-1}; δ 5.42 (1 H, m, 3-H), 3.83 (1 H, m, reduced complexity on D_2O shake, 11-H), 3.50 (2 H, m, 2 × 12-H), 2.60—2.00 (8 H, complex m, reduced to 7 H on D_2O shake, 2 × 10-H + 2 × 4-H + 7β-H + 1-H + 5-H + OH), 1.30 (3 H, s, 3 × 8-H), 1.13 (1 H, d, *J* 8 Hz, 7α-H), and 0.87 (3 H, s, 3 × 9-H).

Compound (37): 0.17 g (19%); spectroscopic data as listed under the $LiAlH_4$ reduction of (1).

Compounds (38)—(41): 0.75 g; tentative structural assignments are based on spectroscopic data: i.r. spectra possessed characteristic hydrocarbon absorption bands only, and ^1H n.m.r. spectra exhibited signals at δ 6.50—5.90 and 5.20—4.90 (=CH) in addition to resonances for the α-pinene moiety.

1,1,1-*Tribromo*-4-*methylpentan*-2-*ol* (43) *from Hydrogenation of Ene Adduct* (42).—A solution of the ene adduct (42) (10.0 g, 29.7 mmol) in ethyl acetate was shaken together with Adam's catalyst (0.1 g) under hydrogen at atmospheric pressure and at room temperature. Hydrogen uptake, to the theoretical value, was complete in 20 min. Filtration through Kieselguhr, removal of the solvent, and distillation of the product under reduced pressure afforded a colourless waxy solid; after recrystalisation from light petroleum (b.p. 40—60 °C) the 1,1,1-*tribromo*-4-*methylpentan*-2-*ol* (43) (8.3 g, 82%) had m.p. 55—57 °C (Found: C, 21.15; H, 3.3; Br, 70.7. $C_6H_{11}Br_3O$ requires C, 21.27; H, 3.27; Br, 70.75%); $\nu_{max.}$ (KBr) 3 350, 2 940, 1 470, 1 390, 1 135, 1 010, 745, and 700 cm^{-1}; δ 3.98 (1 H, dd, separations 2 and 9 Hz, C*H*OH), 3.20 (1 H, s, absent on D_2O shake OH), 2.08—1.54 (3 H, m, CH_2CHMe_2), and 1.06 (6 H, d, *J* 5 Hz, 2 × CH_3).

Reduction of 1,1,1-*Tribromo*-4-*methylpentan*-2-*ol* (43) *with* $LiAlH_4$: *Formation of Compounds* (44)—(50).—To a suspension of $LiAlH_4$ (0.57 g, 15 mmol) in dry ether (20 ml) was added dropwise and with stirring a solution of the bromoalcohol (43) (1.7 g, 5 mmol) in ether (15 ml). The mixture was stirred at room temperature for 4 h and was then quenched and worked up using the same procedure as for the $LiAlH_4$ reduction of (1). After the organic solution had been dried and filtered, the ether was removed by distillation at atmospheric pressure and the residue, after Kugelröhr distillation, afforded the following fractions: (i) 0.30 g, 72 °C/55 mmHg; (ii) 0.16 g, 64 °C/16 mmHg; (iii) 0.10 g, 66 °C/0.01 mmHg. G.l.c./mass spectrometric assay of fraction (i) indicated that the three major products were 4-methylpentan-2-ol (46) and *E*- and *Z*-1-bromo-4-methylpent-1-ene (48) and (49). Two minor components were identified as 4-methylpent-1-ene (50) and 1,1-dibromo-4-methylpent-1-ene (47). Assignments were in accord with the presence of ^1H n.m.r. signals at δ 6.30—5.90 [m, =CH for (48) and (49)], 3.84 [m, C*H*(OH)CH_3 for (46)], and 1.47 [d, *J* 7 Hz, CH(OH)CH_3 for (46)].

Fraction (iii) was composed principally of 1-bromo-4-methylpropan-2-ol (45) and 1,1-dibromo-4-methylpropan-2-ol (44); δ 5.57 [d, *J* 4 Hz, $CHBr_2$ for (44)], 3.90 [m, C*H*OH for (44) and (45)], and 3.50 [m, CH_2Br for (45)].

1,1,1-*Trichloro*-3-{(1S,5S)-6,6-*dimethylbicyclo*[3.1.1]*hept*-2-*en*-2-*yl*}*propan*-2-*yl Acetate* (51).—To the ene adduct (1) from the $TiCl_4$-catalysed addition of chloral to (−)-β-pinene [1] (9.4 g, 33 mmol) in pyridine (3.2 ml) was added dropwise, with stirring, acetic anhydride (3.37 g, 33 mmol). Stirring was continued for 3 h, after which the mixture was diluted with ether (20 ml), and washed with 2M-hydrochloric acid, saturated aqueous sodium hydrogen carbonate, and water. The dried (Na_2SO_4) organic fraction was filtered and the solvent removed under reduced pressure. Distillation of the oily residue at 100—105 °C/0.4 mmHg afforded the *product* as a sweet-smelling colourless oil (6.87 g, 64%); $\nu_{max.}$ (film) 2 890, 1 745, 1 425, 1 365, 1 200, 1 055, 1 025, 940 and 800 cm^{-1}; δ 5.52 (1 H, dd, separations 3 and 10 Hz, 11-H), 5.38 (1 H, m, 3-H), 2.15 (3 H, s, $COCH_3$), 2.0—3.0 (7 H, complex m, ring protons and chain CH_2), 1.32 (3 H, s, 3 × 8-H), 1.04 (1 H, d, *J* 8 Hz, 7α-H), and 0.87 (3 H, s, 3 × 9-H).

Cognate preparation. The 3,3,3-*tribromo-analogue* of (51) was prepared similarly from the ene adduct (34) in 41% yield, b.p. 130—140 °C/1.6 mmHg (Found: C, 36.65; H, 4.25; Br, 51.0. $C_{14}H_{19}Br_3O_2$ requires C, 36.63; H, 4.17; Br, 52.22%).

Epoxide (52).—To a solution of acetate (51) (4.69 g 14.4 mmol) in CH_2Cl_2 (30 ml) was added dropwise, with stirring, a solution of 85% *m*-chloroperbenzoic acid (4.97 g, 28.8 mmol) in CH_2Cl_2 (90 ml). Stirring was continued for 36 h after which the solids were filtered off and the filtrate washed with 10% aqueous sodium sulphite (2 × 10 ml), saturated aqueous sodium hydrogen carbonate (2 × 10 ml), and water (10 ml). After drying (Na_2SO_4), evaporation of the solvent gave the epoxide (52) as a viscous oil which crystallised with time, Recrystallisation from light petroleum (b.p. 40—60 °C) afforded colourless needles (3.64 g, 74%) of the *product*, m.p. 94—95 °C, $[\alpha]_D^{24}$ −0.85 (*c*, 0.2832) (Found: C, 49.35; H, 5.85; Cl, 30.45. $C_{14}H_{19}Cl_3O_3$ requires C, 49.22; H; 5.60; Cl, 31.13); $\nu_{max.}$ (KBr) 2 900, 1 750, 1 375, 1 210, 1 080, 1 030, 810 and 790 cm^{-1}; δ 5.5 (1 H, dd, separations 4 and 8 Hz), 3.3 (1 H, br s), 2.36 (2 H, m), 2.15 (3 H, s), 2.0 (3 H, m), 1.5—1.9 (2 H, m), 1.34 (3 H, s), and 1.0 (3 H, s); δ_C 168.53 (s), 99.94 (s), 77.07 (d), 60.35 (s), 55.14 (d), 44.91 (d), 40.41 (s), 39.71 (d), 35.20 (t), 27.31 (t), 26.67 (q), 25.38 (t), 20.76 (q), and 20.06 (q).

The epoxide prepared by the same route from ene adduct (1) obtained from the thermal addition of chloral to (−)-β-pinene, an 83 : 17 mixture of 11(*R*) : 11(*S*) diastereoisomers, could not be induced to crystallise. It was spectroscopically

identical with the above except for minor differences, *e.g.* δ 3.22 and 3.0 (1 H total, both br s) had intensity ratio *ca.* 4 : 1 (epoxide H).

Cognate preparation. The *tribromomethyl analogue* of (52) was prepared similarly. The pale brown oil (73%) could not be induced to crystallise; $\nu_{max.}$ (film) 2 900, 1 740, 1 450, 1 360, 1 200, 680, and 625 cm^{-1}; δ 5.39 (1 H, dd, separations 4 and 8 Hz), 3.30 and 3.05 (1 H total, 2 × br s, ratio 1 : 3), 2.36 (2 H, m), 2.0 (3 H, m), 1.5—1.1 (2 H, m), 2.20 (3 H, s), 1.34 (3 H, s), and 1.0 (3 H, s). The intensity ratio for the epoxide H was the same as the original diastereoisomeric ratio in the starting material (34) prepared by the $AlCl_3$ catalysed addition of bromal to (−)-β-pinene.

Hydrolysis of the Epoxide (52)→(53)—(55).—The epoxide (52) (1.98 g, 6.05 mmol) was dissolved in a mixture of AnalaR acetone (30 ml) and 1M-hydrochloric acid (10 ml), and the solution stirred for 30 min. Neutralization ($NaHCO_3$) and removal of the acetone under reduced pressure followed by extraction with dichloromethane (3 × 10 ml), drying of the combined organic extracts (Na_2SO_4), and evaporation afforded a colourless oil (2.02 g, 100%). This oil was normally passed on to the next stage without further purification. Its composition was determined as follows:

The oil was shaken with light petroleum (b.p. 40—60 °C) (10 ml) for 30 min and the *ene diol* (53) which crystallised was removed by filtration (1.20 g 55%), m.p. 116—117.5 °C, $[\alpha]_D^{23}$ −17° (*c*, 0.3101) (Found: C, 46.85; H, 5.85; Cl, 28.2. $C_{14}H_{21}Cl_3O_4$ requires C, 46.75; H, 5.88; Cl, 29.57); $\nu_{max.}$ (KBr) 3 370, 3 290, 2 990, 2 910, 2 880, 1 750, 1 220, 1 055, 1 045, and 815 cm^{-1}; δ 5.92—5.76 (2 H, dd superimposed on br s, line separations 3 and 10 Hz, olefinic H and C*H*OAc), 4.16 (1 H, br s, C*H*OH), 2.20 (3 H, s, $COCH_3$), 3.1—1.2 (9 H, 7 H on D_2O shake, complex m, 2 × OH and skeletal H), and 1.27 (6 H, s, 2 CH_3); δ_C 20.76 (q, 2 CH_3), 26.67 (d, ring CH), 27.37 (q, $COCH_3$), 33.27 (t, CH_2CHOH), 37.31 (t, CH_2CH=), 38.36 (t, chain CH_2), 69.00 (d, CHOH), 71.99 (s, CMe_2OH), 81.28 (d, CHOAc), 99.14 (s, CCl_3), 130.70 (d, CH=), 132.51 (s, =C), and 170.46 (s, C=O).

Evaporation of the light petroleum mother liquors afforded a mixture of (54) and (55) with traces of (53) as a colourless, oil (0.76 g, 44%); $\nu_{max.}$ (film) 3 490, 2 905, 1 750, 1 640, 1 220, 1 050, and 805 cm^{-1}; δ 5.80 (2 H, dd superimposed on broad s, C*H*OAc and olefinic H), 4.80 (br s, $=CH_2$), 4.16 (1 H, br s, C*H*OH), 3.1—1.3 (*ca.* 8 H, 7 H on D_2O shake, OH and skeletal H), and 1.8—1.7 (br s, allylic CH_3).

Hydrolysis and Oxidation of the Epoxide (52)→(56)—(58).—The epoxide (52) (1.06 g, 3.24 mmol) was hydrolysed as above, and the mixture of cycloalkenols (53)—(55) (1.13 g) taken up in dichloromethane (4 ml) and added dropwise to a freshly prepared suspension of pyridinium chlorochromate (1.13 g, 5 mmol) in dichloromethane (8 ml). The mixture was stirred for 3 h, diluted with dry diethyl ether, filtered through a pad of Kieselguhr, and evaporated to yield an orange oil (0.98 g), a mixture of cycloalkenones (56)—(58). Pressure column chromatography (ethyl acetate) separated two of the ketones, namely (56) and (57), but generally the mixture of cycloalkenones (56)—(58) was passed on to the next stage without further purification.

The *cyclohexenone* (56) was a white crystalline solid (0.39 g, 34%), m.p. 80—82 °C; $\nu_{max.}$ (KBr) 3 500, 2 990, 1 750, 1 725, 1 665, 1 380, 1 245, 1 210, and 795 cm^{-1}; δ 6.9 (1 H, br m, =CH), 5.6 (1 H, dd, separations 3 and 10 Hz, C*H*OAc), 3.14 (1 H, br d, separation 14 Hz, *H*CH·CHOAc), 2.2—2.8 (7 H, 6 H on D_2O shake, m, ring 5 H + OH + HC*H*·CHOAc), 2.12 (3 H, s, $COCH_3$), and 1.24 (6 H, s, $2CH_3$); δ_C 20.53 (q, $2CH_3$), 26.96 (q, $COCH_3$), 27.49 (t, CH_2CO), 31.58 (t, CH_2CHOAc), 39.36 (t, CH_2C=C), 45.32 (d, $CHCMe_2$), 71.05 (s, Me_2COH), 79.41 (d, CHOAc), 99.35 (s, CCl_3), 133.45 (s, =C·CO), 148.65 (d, CH=), 169.29 (s, $COCH_3$), 198.94 (s, =C·CO).

The *dienone* (57) was isolated as a pale orange oil (0.19 g, 17%); $\nu_{max.}$ 2 990, 1 750, 1 725, 1 675, 1 380, 1 215, and 800 cm^{-1}; δ 6.86 (1 H, m, =CH), 5.58 (1 H, dd, line separations 3 and 10 Hz, C*H*OAc), 4.80 (2 H, m, $=CH_2$), 3.22 (1 H, d, separation 13 Hz, *H*CH·CHOAc), 2.76—2.15 (6 H, complex m, ring 5 H + HC*H*·CHOAc), 2.15 (3 H, s, $COCH_3$), and 1.72 (3 H, br s CH_3C=); δ_C 20.53 (q, CH_3C=), 26.76 (q, $COCH_3$), 31.29 (t, CH_2CO), 31.64 (d, CH_2CHCH_2), 41.64 (t, CH_2-CHOAc), 42.81 (t, CH_2CH=), 79.53 (d, CHOAc), 99.41 (s, CCl_3), 110.82 (t, CH_2=C), 134.03 (s, CH_2=*C*), 146.02 (s, CH=*C*CO), 147.48 (d, *C*H=CCO), 169.18 (s, $COCH_3$), and 198.01 (s, =C·CO).

Hydrolysis, Oxidation and Cleavage of the Epoxide (52)→(59)→(60).—The epoxide (52) (2.04 g, 6.23 mmol) was hydrolysed and the product oxidised by the methods described above. The resulting oil (1.99 g) was taken up in AnalaR acetone (60 ml) and added to a solution of ruthenium tetraoxide prepared by adding sodium metaperiodate (2.0 g) in water (40 ml) to ruthenium dioxide dihydrate (0.35 g) in AnalaR acetone (50 ml). The mixture was stirred, and as the reaction proceeded (fading of reddish yellow colour) further aliquots of sodium metaperiodate solution were added (in all 5 g in 50 : 20 acetone–water) to reoxidise the RuO_2. The mixture was stirred for a total of 5 h, and isopropyl alcohol (10 ml) then added; the solution was filtered, evaporated, and the residue treated with an excess of ethereal diazomethane and allowed to stand overnight. The ether was removed under reduced pressure and distillation at 68—72 °C/0.04 mmHg afforded methyl (*S*)-(−)-4,4,4-trichloro-3-acetoxybutyrate (60) as a pale yellow oil (0.54 g, 33%), $[\alpha]_D^{24}$ −27° (*c* 0.6240) (Found: C, 32.35; H, 3.45. $C_7H_9Cl_3O_4$ requires C, 31.91; H, 3.44%); $\nu_{max.}$ (film) 2 940, 1 755, 1 735, 1 375, 1 290, 1 200, and 805 cm^{-1}; δ 5.96 (1 H, dd, line separations 3 and 9 Hz, C*H*OAc), 3.84 (3 H, s, OCH_3), 3.20 (1 H, dd, line separations 3 and 17 Hz, HC*H*·CHOAc), 2.83 (1 H, dd, line separations 9 and 17 Hz, *H*CH·CHOAc), and 2.16 (3 H, s, $COCH_3$); δ_C 20.53 (q, $COCH_3$), 36.20 (t, CH_2), 52.22 (q, OCH_3), 77.13 (d, CHOAc), 98.89 (s, CCl_3), 168.48 (s, C=O), and 168.94 (s, C=O).

Addition of the chiral shift reagent tris[3-(trifluoromethylhydroxymethylene)-(+)-camphorato]europium(III), Eu(tfc)$_3$, to the ^1H n.m.r. sample resulted only in the downfield shift of the resonances without splitting any of the signals when the original starting material (1) was obtained from the $TiCl_4$-catalysed addition of chloral to (−)-β-pinene. On the other hand, when the starting material (1) originated from the thermal ene addition of chloral to (−)-β-pinene [a 83 : 17 mixture of the 11(*R*) : 11(*S*) isomers], the ^1H n.m.r. spectrum of the derived ester (60) was affected by the addition of Eu(tfc)$_3$ and marked broadening of the various resonances, with splitting of the δ 5.96 signal into eight peaks, was observed. This, together with the Eu(tfc)$_3$ data on the (±)-ester (60), below, indicated that the stereochemical integrity of the exocyclic chiral centre in (1) was unchanged by its transformation into (60).

Methyl (±)-4,4,4-*Trichloro*-3-*acetoxybutyrate* (60).—The hexene–chloral ene adduct (2) (2.02 g, 8.6 mmol) was treated with acetic anhydride in pyridine, as above in the preparation of (51), to give the acetoxy derivative (1.94 g, 82%), b.p. 62—64 °C/0.5 mmHg; $\nu_{max.}$ (film) 2 900, 1 745, 1 430, 1 370, 1 210, 1 065, 975, 940, and 790 cm^{-1}. Cleavage was effected by the RuO_4 procedure detailed above in the preparation of (−)-(60), and the *racemic ester* (60) (0.67 g, 37%) so obtained

was found to be spectroscopically identical with the optically active form. Addition of $Eu(tfc)_3$ to the ^1H n.m.r. sample of (±)-(60) produced broadening of all signals and a splitting of δ 2.16 signal ($COCH_3$) into a fine doublet and the 5.96 signal (C*H*OAc) into eight peaks; integration confirmed the 1 : 1 distribution of enantiomers.

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