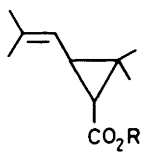
Mechanistic Study of the Thermal Acid-catalysed Rearrangement of *trans*-methyl Chrysanthemate to Lavandulyl Derivatives†

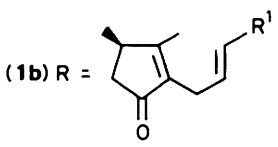
Zeev Goldschmidt* and Bernard Crammer
Department of Chemistry, Bar-Ilan University, Ramat Gan 52100, Israel
Raphael Ikan
Department of Organic Chemistry, Hebrew University of Jerusalem, Jerusalem 91904, Israel

trans-Methyl chrysanthemate (**17**) under acid conditions at room temperature rearranged to the lavandulyl esters: methyl *trans*-5-methyl-2-propen-2-ylhex-3-enoate (**18**) and methyl *trans*-5-methyl-2-(2-hydroxypropan-2-yl)hex-3-enoate (**19**) which was formed by a cyclopropylcarbinyl–homoallyl rearrangement. Both (**18**) and (**19**) further isomerise and dehydrate to the stable methyl *trans*-5-methyl-2-propan-2-ylidenehex-3-enoate (**20**). Under similar acidic conditions, (**18**) and (**19**) each gave a mixture of lavandulyl esters and (**17**); minor amounts of side products, methyl *trans*-5-methylhex-3-enoate (**21**), methyl *trans*-5-methyl-2-(2-methoxypropan-2-yl)hex-3-enoate (**22**), methyl *cis*-5-methyl-2-propen-2-ylhex-2-enoate (**23**) were detected after some time. Acid methanolysis of (**17**) gave a substantial amount of (**22**) and its isomer, methyl 2,2-dimethyl-3-(2-methoxypropan-2-yl)cyclopropanecarboxylate (**26**). There was also found in low concentration, methyl *trans*-5-methyl-2-propan-2-ylhex-3-enoate (**24**) and methyl 5-methyl-2-propan-2-ylidenehexanoate (**25**) possibly the result of a hydride transfer from the solvent. Deuterium exchange was observed in the isobutenyl side-chain of (**17**) and the isobutenyl moiety of (**18**) and (**19**). At 130 °C under similar acidic conditions a mixture of unsaturated γ- and δ-lactones was obtained from (**17**). The principal lactone was dihydro-5-propan-2-yl-3-propan-2-ylidenefuran-2(3*H*)-one (**29**). Mechanisms for the formation of these products are discussed. The fact that lavandulyl derivatives were obtained may shed new light on the biogenesis of chrysanthemic acid in plants.

The irregular monoterpene, *trans*-chrysanthemic acid (**1a**) is the biogenetic precursor of the insecticidal chrysanthemyl esters



(**1a**) R = H



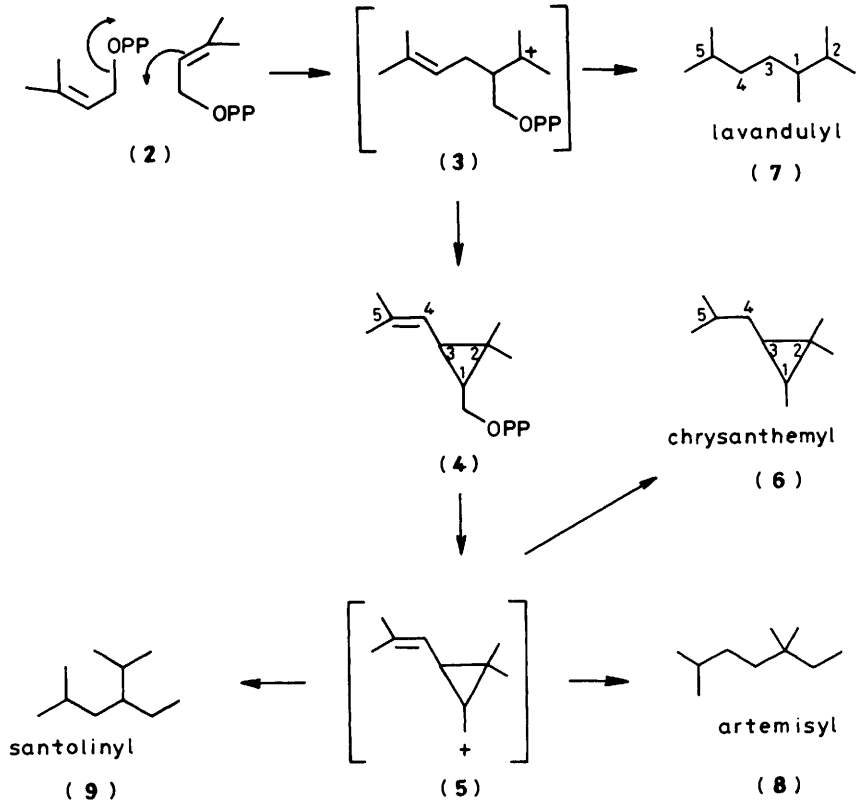
(**1b**) R =

$R^1 = CH_2{=}CH-$	Pyrethrin I
= Me	Cinerin I
= Et	Jasmolin I

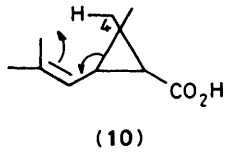
(**1b**) which occur naturally in pyrethrum (*Chrysanthemum cinerariaefolium*).[1] It has been suggested that the acid (**1a**) is biosynthetically formed by a three-step route involving the initial non-head-to-tail combination of two molecules of dimethylallyl pyrophosphate (**2**) to form chrysanthemyl pyrophosphate (**4**) by a mechanism involving a 1,3 elimination of pyrophosphoric acid *via* the intermediate (**3**). The pyrophosphate ester (**4**) is then oxidised to chrysanthemic acid (**1a**).[2] It has also been proposed that (**4**) is a key intermediate in the biogenesis of other irregular monoterpenes having artemisyl[3] (**8**) and santolinyl[4] (**9**) carbon skeletons. Biosynthetic and chemical evidence suggests a mechanism of acid-catalysed cyclopropylcarbinyl–homoallyl rearrangement which converts (**4**) *via* the carbocation (**5**) into (**8**) and (**9**) by cleavage of the 1,3- and 1,2-cyclopropane bonds respectively[5] (Scheme 1).

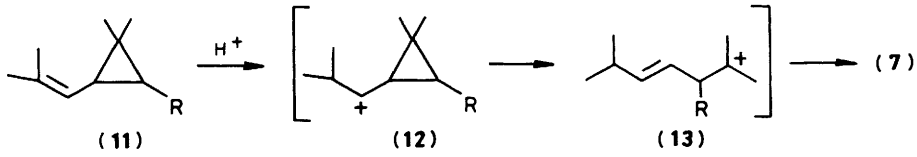
It is clear that lavandulyl (**7**) monoterpenes cannot be interrelated to other irregular monoterpenes by a mechanism involving the same cyclopropylcarbinyl cation (**5**). Previously Crombie *et al.* had showed that *trans*-cyrsanthemyl alcohol (**14**) or its methyl ether (**15**) (Scheme 2) gave only artemisia derivatives.[5] However, buttressed by previous chemical models, three biogenetic pathways for the chrysanthemyl (**6**) to lavandulyl (**7**) might be postulated. (i) Cleavage of the C(2)–C(3) bond of (**4**) by protonation at C-3 of the cyclopropane ring will lead directly to the lavandulyl cation (**3**), the same intermediate which has been proposed as the initial product of the prenyl transfer reaction of irregular terpenes.[2,7] The direct protonation of cyclopropanes has been thoroughly studied [8] and has been recently proposed as a biogenetic route for the interconversion of irregular monoterpenes.[9] However, it is unlikely to occur in the presence of the more active carbinol and olefinic sites. (ii) A non-ionic one-step cleavage of the cyclopropane ring *via* a thermal homo 1,5-sigmatropic hydrogen shift (**10**).[10] Although this reaction has been studied on a variety of chrysanthemyl derivatives [5,10,11] it is doubtful whether it occurs biogenetically since relatively high temperatures are usually required. (iii) A two-step ionic reaction involving an initial protonation of a chrysanthemyl derivative (**11**) at the isopropylidene carbon atom forming the cyclopropylcarbinyl cation (**12**) which then readily rearranges to the lavandulyl cation (**13**). Surprisingly, this attractive mechanism has been hitherto reported only for chrysanthemyl derivatives where the isopropenyl side-chain is functionalised with at least one hydroxy group.[5,12]

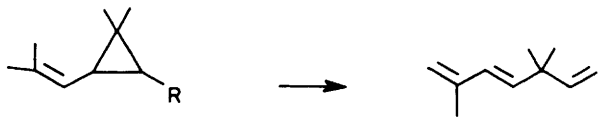
† Poster communication: Z. Goldschmidt, B. Crammer, and R. Ikan, Progress in Natural Product Chemistry, The Royal Society of Chemistry, Perkin Division, Nottingham, July, 1982.



Scheme 1.



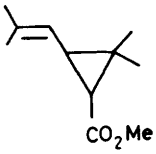




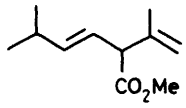
(1a) R = CO_2H
(14) R = CH_2OH
(15) R = CH_2OMe
(16) R = CN

Scheme 2.

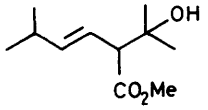
We now report that under mild acidic conditions at room temperature *trans*-methyl chrysanthemate (**17**) undergoes smooth rearrangement to give only lavandulyl derivatives. In fact the methyl lavandulyl esters (**18**) and (**19**) are the only primary products initially detected at room temperature. We also provide evidence for a mechanism which involves protonation of the double bond of (**17**) followed by a cyclopropylcarbinyl–homoallyl rearrangement.



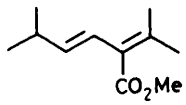
(**17**)



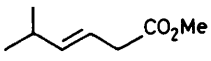
(**18**)



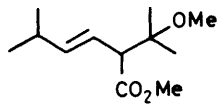
(**19**)



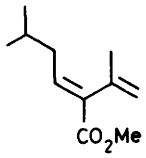
(**20**)



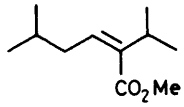
(**21**)



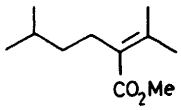
(**22**)



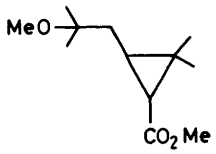
(**23**)



(**24**)



(**25**)



(**26**)

Results and Discussion

Knowing that Pattenden and Otieno [10] had obtained a complex mixture of lavandulylic acid derivatives among other products from (**1a**) under strong acidic conditions and at high temperature, we decided to follow the course of the two-phase reaction of (**17**) at room temperature for extended periods. The reaction was monitored by high resolution n.m.r. spectrometry and the lavandulyl esters were isolated by g.l.c. on a Carbowax preparative column.

When (**17**) was efficiently stirred in a mixture of pentane and 50% aqueous sulphuric acid at room temperature mixtures of methyl lavandulyl esters of varying composition were obtained. Flash column chromatography afforded the pure unsaturated hydroxy ester (**19**) ($\nu_{max.}$ 3 510 and 1 730 cm^{-1}; molecular formula $C_{11}H_{20}O_3$ from elemental analysis). The mass spectrum showed a strong fragment of *m/z* 142 suggesting the loss of acetone *via* a retrograde aldol cleavage. The n.m.r. spectrum revealed the presence of a *trans*-disubstituted double bond at lowfield (J_{vic} 15.3 Hz) flanked by an isopropyl group and a methine carbon α to the ester whose proton resonates at δ 2.96 p.p.m. Two diastereotopic methyls α to the OH resonate at δ 1.23 and 1.18. The broad singlet of the hydroxy proton at δ 3.17 disappeared in the presence of D_2O. The spectral data confirmed the product to be methyl *trans*-5-methyl-2-(2-hydroxypropan-2-yl)hex-3-enoate.[14] Shirley *et al.*[14] reported a *cis*/*trans* mixture of the hydroxy lavandulyl ester obtained by an aldol condensation of *cis*/*trans* (**21**) and acetone. The methyl ester, methyl *trans*-5-methyl-2-propen-2-ylhex-3-enoate (**18**) which was eluted first by g.l.c. showed a molecular ion at *m/z* 182 corresponding to $C_{11}H_{18}O_2$. The i.r. data indicated a non-conjugate ester ($\nu_{max.}$ 1 735 cm^{-1}) containing a terminal methylene group ($\nu_{max.}$ 3 080, 1 645, and 895 cm^{-1}) and a *trans*-disubstituted double bond ($\nu_{max.}$ 970 cm^{-1}). The n.m.r. spectrum revealed a similar spectrum to (**19**) except that instead of the two diastereotopic methyls there was a vinylic methyl at δ 1.75 p.p.m. and two methylene proton signals at δ 4.87 and 4.89. The acid corresponding to (**18**) had been previously proposed by Pattenden and Otieno.[13] The third lavandulyl ester which became the principal product after some time has an n.m.r. spectrum which closely resembled the corresponding acid previously reported except for the methyl ester signal at δ 3.81. The spectral and analytical data confirmed this lavandulyl ester to be methyl *trans*-5-methyl-2-propan-2-ylidenehex-3-enoate (**20**).[12] It should be noted that the *cis*-methyl chrysanthemate was not detected at any stage of the reaction since we did not detect in the n.m.r. spectrum of the mixture the characteristic methyl ester singlet at δ 3.64. After longer reaction time a number of side products were detected in low yield of which six were identified as (**21**), (**22**), (**23**), (**24**), (**25**), and (**36**). The ester (**21**) was obviously derived from (**19**) by a retrograde aldol cleavage. Its mass spectrum showed a strong molecular fragment at *m/z* 142 and the fragmentary pattern was very similar to (**19**). The ^1H n.m.r. spectrum was also similar to (**19**) except that a two-proton signal of the methylene group appears at δ 3.03 instead of the two methyl signals at δ 1.18 and 1.23. The spectral data indicate the volatile ester (**21**) to be methyl *trans*-5-methylhex-3-enoate.[14]

The presence of the methoxy lavandulyl ester (**22**) was detected in the n.m.r. spectrum and confirmed from an independent reaction of (**17**) in 50% methanolic sulphuric acid. The n.m.r. spectrum was similar to that of the hydroxy lavandulyl ester (**19**) except that, instead of the hydroxy group at δ 3.17 there was a singlet for three protons at δ 3.23. It is clear that this ester was obtained from (**19**) and methanol [released from the hydrolysis of (**20**)]. The methanolic acidic conditions also revealed a new methyl ester (**26**) from the n.m.r. spectrum of the reaction products. The ester (**26**) was isomeric to that of the methoxy lavandulyl ester (**22**) except that the n.m.r. spectrum showed an entirely different picture. There were no vinylic signals but a singlet for six protons at δ 1.17 for the two methyls of the side chain as well as two methyl groups attached to the cyclopropane ring at δ 1.23 and 1.13. The two doublets of doublets at δ 1.16 and 1.51 (*J* 14 Hz) correspond to the diastereotopic methylene hydrogens. The two remaining hydrogens at δ 1.41 and δ 1.19 p.p.m. confirms the cyclopropane structure (**26**) previously reported by Harper and Reed.[15] This ester (**26**) was also obtained in 44% yield from (**17**) and 5% methanolic sulphuric acid under reflux for 24 h.

A further methyl ester was detected from the reaction mixture after some time and in very low concentration. Its structure was established from its n.m.r. spectrum which revealed a triplet at lowfield centred at δ 6.81. The remaining signals are similar to the isopropyl and propenyl signals observed in the lavandulyl ester (**18**). The *cis*-configuration of this ester (**23**) was inferred from Pascual's method of determining the chemical shift of the hydrogen in trisubstituted olefins.[16] The last two methyl lavandulyl esters (**24**) and (**25**) were detected with difficulty

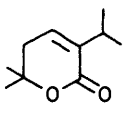
Table 1. Percentage composition of methyl esters and lactones at 130 °C

Reaction time (h)	(17)	(18)	(19)	(20)	(27)	(28)	(29)	(30)	*
1	33	22	4	11	10	5	10		5
48					14	12	55	10	9

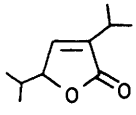
* Products unassigned.

after some time. It was found that if (**17**) was subjected to 50% methanolic sulphuric acid and pentane for 23 days at room temperature, it gave sufficient of the esters (**24**) and (**25**) for spectral analysis. The g.c./mass spectrometry gave for each isomer a strong molecular ion of 184 which suggests a reduction of a double bond of one of the lavandulyl esters (**18**), (**20**), or (**23**). The i.r. spectrum of a pure sample of (**24**) was consistent with that for an unsaturated ester ($\nu_{max.}$ 1 715, 1 640, and 810 cm^{-1}) and its ^1H n.m.r. spectrum was closely similar to that for the *cis*-methyl lavandulyl ester (**23**) except for replacement of the propenyl function by a propyl group. A split triplet centred at δ 5.73 (*J* 7.5 Hz) for the *trans*-vinyl proton together with the two isopropyl groups confirmed that the ester (**24**) was methyl *trans*-5-methyl-2-propan-2-ylhex-2-enoate. The ^1H n.m.r. spectrum of the isomer (**25**) showed no olefinic hydrogens but two methyl singlets at δ 1.94 and 1.80 for a propylidene group and two multiplets each of two hydrogens centred at δ 2.27 and 1.24 clearly indicated that the ester (**25**) was methyl 5-methyl-2-propan-2-ylidenehexanoate. Although it is not clear how these two isomeric lavandulyl esters were obtained it is reasonable to assume that one of the double bonds of one of the methyl esters (**18**), (**20**), or (**23**) was reduced followed by a shift of the double bond to yield the methyl lavandulyl esters (**24**) and (**25**).

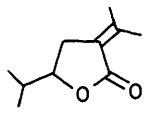
On the other hand if (**17**) in heptane is heated to 130 °C in the presence of 50% aqueous sulphuric acid the products formed are more complex. After 1 h 67% of the starting material (**17**) had been consumed undergoing rearrangement and lactonisation to give a mixture of methyl lavandulyl esters and unsaturated γ- and δ-lactones. The n.m.r. spectrum of the reaction products disclosed four methyl esters (**17**), (**18**), (**19**), and (**20**). (See Table 1). From g.c./mass spectrometry evidence supplemented by spectral results the unsaturated β-lactone (**27**) and three unsaturated γ-lactones (**28**), (**29**), and (**30**) were also



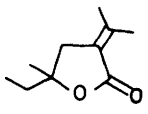
(**27**)



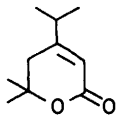
(**28**)



(**29**)



(**30**)



(**31**)

detected. The principal lactones, each in 10% yield, were the pentenolide (**27**) and the butanolide (**29**). It should be noted that Pattenden and Otieno [10] had previously isolated the isomeric δ-lactone (**31**) and the γ-lactone (**29**) as two of the lactones obtained from heating *trans*-chrysanthemic acid (**1a**) with pyridine–HCl at 210 °C. The ^1H n.m.r. spectrum of (**27**) revealed a doublet of triplets centred at δ 6.42 (*J* 4.5 and 1.3 Hz)

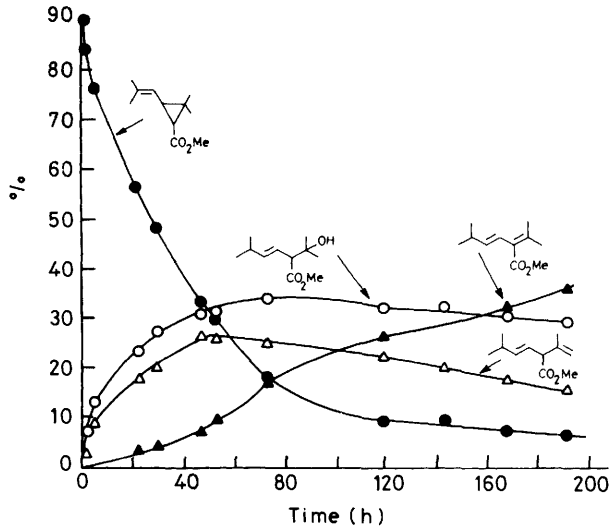


Figure.

for the vinyl hydrogen and a split doublet at δ 2.42 (*J* 4.5 Hz) for the methylene hydrogens; the latter on decoupling gave a singlet at δ 6.42. The singlet at δ 1.42 represents the gem dimethyl groups and an isopropyl doublet at δ 1.10 (*J* 6.7 Hz). The ^1H n.m.r. spectrum of the third lactone (**28**) was very simple since it consisted solely of isopropyl group signals at δ 1.18 (*J* 6.7 Hz) and 0.98 (*J* 7.0 Hz) and ring proton signals centred at δ 6.60 and 4.69. Together with the mass spectrum which showed a molecular ion at *m/z* 168 structure (**28**) was therefore secured. The ^1H n.m.r. spectrum of the fourth γ-lactone should show signals assignable to an isopropyl group but instead, a quartet centred at δ 1.67 (*J* 7.3 Hz) and a triplet centred at δ 0.94 (*J* 7.3 Hz) confirmed the presence of an ethyl group. The additional methyl signals at δ 1.36, 1.85, and 2.26 allowed the assignment of structure (**30**) to this lactone. After 48 h all the methyl lavandulyl esters had disappeared only a mixture of γ- and δ-unsaturated lactones being observed; the principal one (**29**), in 55% yield, was thermodynamically the most stable lactone. It is known that δ-lactones are isomerised to γ-lactones under acidic conditions.[17]

Inspection of the carbon skeleton of the unsaturated esters and lactones obtained by the acid-catalysed rearrangement of *trans*-methyl chrysanthemate (**17**) clearly shows that they must all be derived by a mechanism involving cleavage of the C(2)–C(3) cyclopropane bond to give lavandulyl derivatives. The γ-lactone (**30**) was obviously formed from a further skeletal rearrangement presumably *via* a Wagner-Meerwein 1,2-methyl migration.[18]

As shown in the Figure the concentration of both methyl lavandulyl esters (**18**) and (**19**) increases initially faster than that of the more stable ester (**20**), the rate of formation of the hydroxy ester (**19**) being approximately twice as fast as that of (**18**). The concentration of the lavandulyl esters (**18**) and (**19**) reaches a maximum after 60 h and then decreases with a gradually concomitant accumulation of the ester (**20**). This is the behaviour that would be expected if (**18**) and (**19**) were intermediates to the conjugate lavandulyl ester (**20**) in a stepwise reaction.

The three esters (**17**), (**18**), and (**19**) eventually form an equilibrium mixture which subsequently produces the more stable conjugate ester (**20**) (see Figure). The equilibrium position cannot be accurately determined under these conditions both because of the side reactions that occur between (**18**) and (**19**) and the low concentration of the *trans*-

Table 2. Relative concentration of methyl esters obtained by reaction of the lavandulyl methyl ester (**19**) in 50% aqueous sulphuric acid and hexane at room temperature.

Reaction time (h)	(**17**) δ 3.67*	(**18**) δ 3.70	(**19**) δ 3.72	(**20**) δ 3.81
49	3	5	74	18
97	6	17	45	32

Table 3. Relative concentration of methyl esters obtained by reaction of the lavandulyl methyl ester (**18**) in 50% aqueous sulphuric acid and hexane at room temperature.

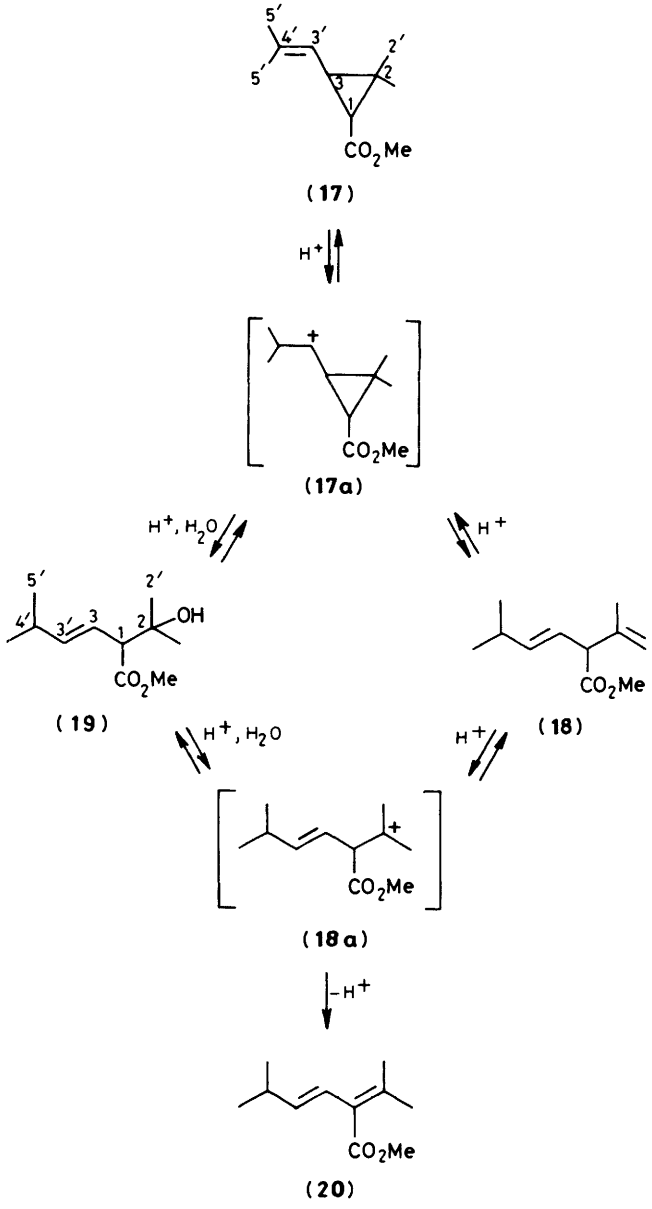
Reaction time (h)	(**17**) δ 3.67	(**18**) δ 3.70	(**19**) δ 3.72	(**20**) δ 3.81
6	2	78	19	1
23	6	17	50	27

*Chemical shift of CO_2Me in the n.m.r. spectrum.

methyl chrysanthemate (**17**); in the equilibrium mixture the approximate ratio of compounds is 1(**17**):2(**18**):4(**19**) (see Figure). It is important to note the differences in the relative concentrations of (**20**) in the product mixtures derived from the various methyl esters prior to equilibration. Starting from (**17**) it can be seen from the Figure that the accumulation of the less stable lavandulyl ester (**18**) and the hydroxy ester (**19**) is more rapid than that of (**20**). On the other hand, under the same conditions, the hydroxy ester (**19**) dehydrates preferentially to the more stable ester (**20**) (Table 2). Inspection of Table 3, however, reveals that the isomerisation of the non-conjugated ester (**18**) to the conjugated ester (**20**) proceeds much slower than its hydration to (**19**) but, as in the previous cases, eventually reaches equilibrium. Furthermore, the non-conjugated lavandulyl ester (**18**) under the given acidic conditions reaches an equilibrium state in approximately one quarter of the time needed by the hydroxy ester (**19**). Finally we wish to emphasise that to our knowledge this is the first example in which a chrysanthemate is obtained from a lavandulyl ester. These results are consistent with the mechanism presented in Scheme 3 which involves the cyclopropylcarbinyl cation (**17a**) and the homoallylic carbonium (**18a**) as the two intermediates in the stepwise reaction leading to (**20**). Thus the carbonium ion (**17a**), formed by protonation of (**17**) at the C-4′ position, undergoes two reversible bimolecular ring-opening reactions with water: (i) a nucleophilic attack at C-2 of the cyclopropane ring to rearrange to (**19**) and (ii) proton abstraction from a 2′-methyl to afford the non-conjugated diene ester (**18**). Since none of the more stable conjugated lavandulyl ester (**20**) is initially formed we conclude that proton abstraction from the C-1 position of (**17**) is, as expected, highly unfavourable. The next step in the formation of the ester (**20**) requires the intermediate (**18a**) to either capture a water molecule to produce the hydroxy ester (**19**) or eliminate a β-proton to afford the isomeric esters (**18**) and (**20**). However, unlike (**17a**) which cannot deprotonate to (**20**), the carbonium ion (**18a**) deprotonates, as expected according to the Saytzev Rule,[19] preferentially to (**20**). Hydration of (**18a**) like that of (**17a**) remains faster than deprotonation[20] (Table 2).

It should be noted that although a direct equilibrium between the two carbonium ions (**17a**)⇌(**18a**) is not included in Scheme 3 such an interconversion cannot be entirely excluded. However, our results strongly indicate that such an interconversion is much slower than the alternative bimolecular reactions.

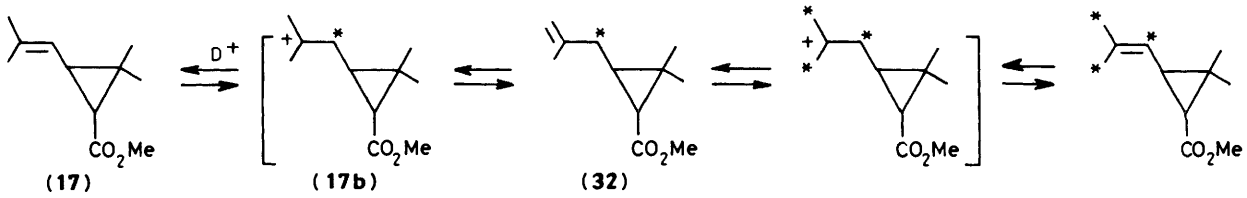
Other irreversible side reactions which compete with the



Scheme 3. Mechanism of the acid-catalysed rearrangement of *trans*-methyl chrysanthemate to lavandulyl methyl esters

formation of (**20**) are the retrograde aldol cleavage of the hydroxy ester (**19**) to acetone (not isolated) and the methyl *trans*-5-methylhex-3-enoate (**21**),[14] the isomerisation of the non-conjugate ester (**18**) to the *cis*-conjugated ester (**23**), and the partial reduction to give the isomeric esters (**24**) and (**25**). These methyl lavandulyl esters were probably formed by a hydride transfer reaction, commonly observed in strongly acidic hydrocarbon solutions.[21]

Treatment of (**17**) with a 50% D_2SO_4–D_2O mixture revealed the presence of yet another carbonium intermediate, (**17b**), in the reaction mixture; this eventually led to deuterium exchange at positions 3′ and 5′ of the isobutenyl side chain of (**17**) by a mechanism depicted in Scheme 4. This process is extremely rapid compared with the ring-opening reactions since (**17**) is already completely deuteriated in the side chain when less than 10% of the lavandulyl esters are formed. Consequently the lavandulyl esters (**18**), (**19**), and (**20**) were also labelled at the corresponding isopropenyl positions, C(3′)—C(5′). Notably

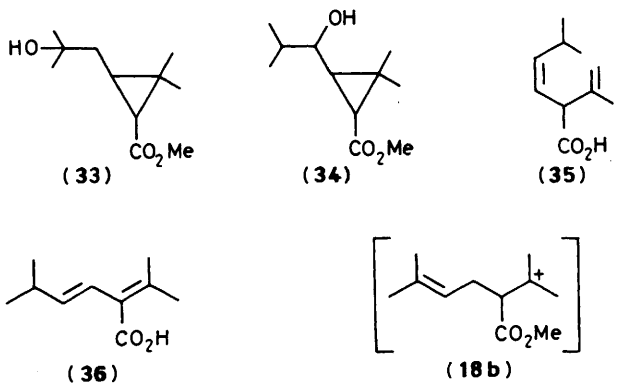


Scheme 4. Stepwise deuterium exchange at the isobutenyl side-chain of *trans*-methyl chrysanthemate in the presence of D_2O–D_2SO_4.

however, none of the other protons in *trans*-methyl chrysanthemate (**17**) nor in the lavandulyl esters was exchanged to a significant extent (<5%, as determined by relative peak integration in the n.m.r. spectrum). In contrast, treatment of (**18**) with a 50% mixture of D_2SO_4–D_2O under the same conditions resulted in only *ca.* 15% deuterium exchange at the 2′-methyls of (**19**) and 10% exchange at the C-1 isopropenyl moiety of (**18**). No deuterium was detected elsewhere. These results imply that deprotonation of (**18a**) to (**18**) is slow compared with its hydration to (**19**). The lavandulyl ester (**18**) is thus expected to decrease more rapidly than the hydroxy lavandulyl ester (**19**) in the reaction of (**17**) as indeed can be seen in the Figure. Furthermore, it appears that there is no appreciable conversion of (**18**) and (**19**) into the chrysanthemate ester (**17**) since no deuterium exchange was detected in positions C(3′)—C(5′) of these lavandulyl esters.

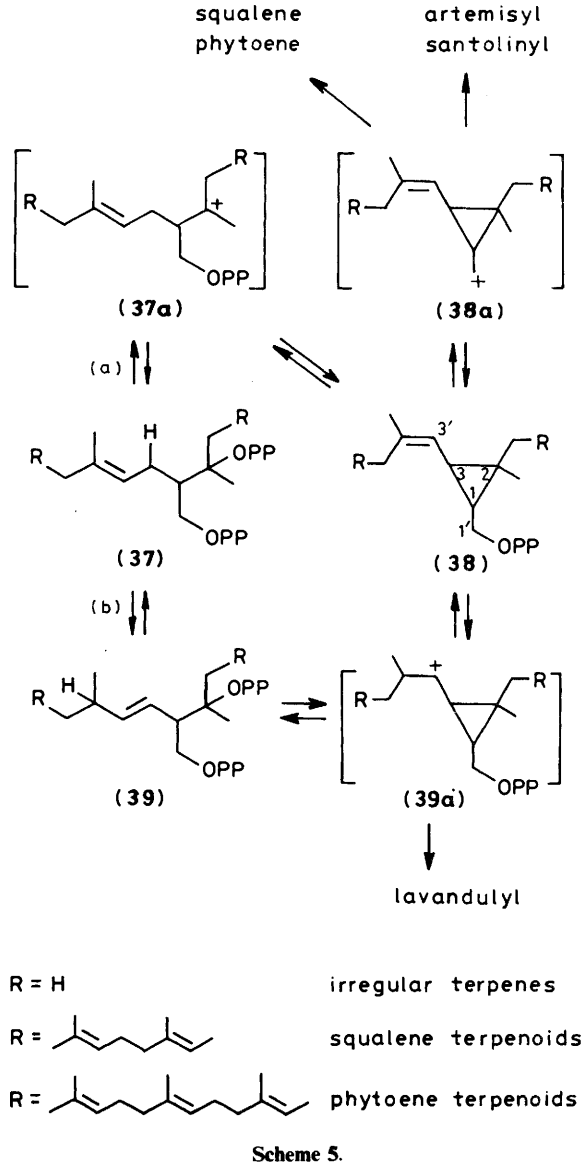
Although it seems clear that the deuteriation of (**17**) proceeds *via* the intermediate (**17b**) none of the isomeric olefin (**32**)[22] (Scheme 4) nor the tertiary alcohol (**33**) were detected, apparently because of the rapid interconversion back to the methyl chrysanthemate (**17**). This may also be the reason that the cyclopropylcarbinol (**34**) was not observed. It was, however, found that (**17b**) could be trapped by acidic methanolysis of (**17**) to give the methoxycyclopropane ester (**26**) [together with isomeric lavandulyl methoxy ester (**22**)]. This methoxy ester (**26**) was identical with the one previously isolated as a side product of the Clinton esterification of chrysanthemic acid.[15] In fact, the methanolysis of (**17**) under Clinton's conditions [23] gave a high yield of (**26**) (See Experimental section).

Two alternative mechanisms involving cleavage of the C(2)–C(3) cyclopropane bond should be mentioned. The first mechanism, suggested by Pattenden for the chrysanthemic acid rearrangement in the presence of pyridine hydrochloride at 210 °C, involves the symmetry-allowed thermal 1,5-H shift (**10**)[24] to form the *cis*-dienoic acid (**35**) which then isomerises to



(**36**).[10] In view of the mild conditions (room temperature and two phases) carried out by us and the observation of deuterium exchange at the C-4′ position of the esters (**18**) and (**19**) derived from (**17**) in deuteriated acidic media it is not feasible that this mechanism operates under our conditions.

The second mechanism which may be considered, involves cleavage of the C(2)–C(3) cyclopropane bond by initial protonation of (**17**) at C-3 eventually leading to (**18**) and (**19**) *via* the carbonium ion intermediate (**18b**). The protonation of the C(1)–C(2) and C(1)–C(3) bonds of chrysanthemic acid has been previously invoked by Pattenden. Under deuteriated conditions such a cleavage is expected to lead to deuterium



Scheme 5.

exchange at C-3 of the lavandulyl esters. Since none was observed this mechanistic route may also be abandoned.

In concluding we should point out the importance of the reaction conditions and the nature of the acid catalyst in controlling the rearrangement of chrysanthemic acid derivatives. While our reaction conditions caused specific protonation at the most reactive site of the chrysanthemyl molecule namely, the side-chain double bond, more drastic conditions such as high temperature and pyridine hydrochloride catalyst, being obviously less selective, may lead to protonation of the cyclopropane ring.

It has long been suggested[25,26] that the biogenesis of the irregular terpenes (C_{10}) is similar to that outlined for squalene (C_{30}) and phytoene (C_{40}) terpenoids.[2] Scheme 5 shows the two general routes proposed for the biosynthesis of these terepene prenylogues. Both differ in the mechanism of the cyclopropanation reaction or, conversely, by the ring cleavage of the vinylcyclopropane intermediate (**38**) [chrysanthemyl-OPP for R = H; presqualene for R = $C_{10}H_{17}$]. Route (a) adopted by Epstein and Poulter [2] for the biosynthesis of monoterpenes, anticipates a one-step acid-catalysed 1,3(W)-elimination to give (**38**), presumably *via* a carbonium ion intermediate (**37a**). The reverse cleavage of the cyclopropane ring to lavandulol by protonation was tentatively suggested by Banthorpe *et al.*[9] The two-step route (b) was favoured by van Tamelen and Schwartz[26] for the biosynthesis of presqualene. A double-bond isomerisation first takes place to give the homoallylic system (**39**) which is well known to cyclise reversibly to (**38**) presumably *via* the cyclopropylcarbonium ion (**39a**). Recently it has been suggested by Whiting *et al.*[14] that if 'pre-presqualene', (**39**; R = $C_{10}H_{17}$), is a precursor to presqualene, then 'pre-chrysanthemyl-OPP', (**39**; R = H), could be an intermediate in the biosynthesis of chrysanthemyl-OPP (**38**; R = H). Our present study strongly supports this premise by demonstrating that acid-catalysed ring cleavage of chrysanthemate occurs specifically *via* a cyclopropylcarbinyl–homoallyl rearrangement and not by direct ring protonation. Furthermore, demonstrating that this rearrangement is reversible makes the analogous biosynthetic pathway (b) more feasible than the alternative 1,3-elimination–cyclopropane protonation pathway (a).

Experimental

General.—^{1}H N.m.r. spectra were recorded on a Bruker WX 300 spectrometer using 5 μl of the sample per 300 μl of $CDCl_3$ solution. Deuterium lock was provided by the solvent ($CDCl_3$) and tetramethylsilane (TMS) as the internal standard. Splittings (*J*) are given in Hz. I.r. spectra were measured on a Perkin-Elmer Model 157G. Preparative g.l.c. separations were carried out on a F and N Model 720 dual column programmed-temperature gas chromatograph (equipped with both thermal conductivity and flame ionization detectors). The separations were achieved on a 2 m 10% OV 17 on Chromosorb W. The conditions were: detector temperature 300 °C, inlet temperature 245 °C, rate 5 °C/min, programmed from 20—205 °C. Molecular weights were determined from mass spectra measured on a Finnigan Model 4021 Gas Chromatograph Mass Spectrometer with data system. The conditions used for the g.c./mass spectrometry were on a XE-60 column, programmed 50—180 °C at 5 °C/min. Elemental analyses were carried out at the analytical laboratories of the Hebrew University of Jerusalem.

trans-*Methyl Chrysanthemate* (**17**).—Ethyl chrysanthemate used was commercially available (Aldrich) containing a racemic mixture of 4:6 *cis*:*trans* isomers. *cis*:*trans*-Chrysanthemic acid (obtained from alkaline hydrolysis of *cis*:*trans*-ethyl chrysanthemate) (79.5 g, 0.47 mol) and anhydrous zinc chloride (11 g) in ethylene dichloride (190 ml) were stirred for 19 h at 80 °C. The cooled mixture was stirred with saturated aqueous ammonium chloride (100 ml) for 10 min. The organic layer was separated and extracted with three portions (100 ml, 2 × 50 ml) of 10% aqueous potassium hydroxide to remove the *trans*-chrysanthemic acid. The organic layer contained the δ-lactone of *cis*-chrysanthemic acid. The potassium chrysanthemate solution was stirred with activated carbon for 15 min at 60 °C, filtered, cooled to room temperature, and acidified with 25% aqueous hydrochloric acid. The chrysanthemic acid (**1a**) was extracted with methylene chloride (4 × 50 ml) and the solvent removed to afford the crude red product (42.6 g, 54%) which was distilled as a colourless oil, b.p. 106 °C (1 mmHg) (32.3 g); it crystallised with time and had m.p. 50—52 °C (lit.,[15] 54 °C) (Found: C, 71.3; H, 9.35. Calc. for $C_{10}H_{16}O_2$: C, 71.39; H, 9.58%). The spectral data were identical with those in the literature.[27] (The ^{1}H n.m.r. spectrum revealed that the acid was 100% *trans*-chrysanthemic acid.) The methyl ester (**18**) was prepared according to Clinton and Laskowski[23] in 82% yield; δ_H 4.89 (1 H, dm, *J* 7.9 Hz), 3.67 (3 H, s), 2.06 (1 H, t, *J* 7.9 and 5.4 Hz), 1.70 (6 H, s), 1.39 (1 H, d, *J* 5.4 Hz), 1.26 (3 H, s), and 1.13 (3 H, s). The ^{1}H n.m.r. spectrum of the distilled ester (**18**) revealed the lavandulyl methyl ester (**19**) as an impurity (3.2%).

Rearrangement of trans-*Methyl Chrysanthemate.* (**17**).—A mixture of *trans*-methyl chrysanthemate (3 ml) and 50% aqueous sulphuric acid (3 ml) in pentane (10 ml) was stirred at room temperature; 0.4 ml portions of the mixture were removed at intervals of time and the pentane evaporated by nitrogen. The residual oils were analysed according to the intensities of the chemical shifts of each methyl ester in the n.m.r. spectrum (see Figure).

Methyl trans-5-Methyl-2-(2-hydroxypropan-2-yl)hex-3-enoate (**19**). Compound (**17**) (3.5 ml) in hexane (10 ml) was stirred with 50% aqueous sulphuric acid (3 ml) at room temperature for 117 h. Work-up gave an oil (2.6 ml) of composition (**17**) 11%, (**18**) 17%, (**19**) 53%, (**20**) 10%, and (**21**) 9%. Flash column chromatography of this on silica gel [hexane–ethyl acetate 95:5 as eluant] yielded (a) a mixture of lavandulyl methyl esters and (**17**) and (b) the hydroxy lavandulyl ester (**19**) (1.2 ml).

Lactonisation of (**17**).—Compound (**17**) (2 ml) was added to a stirred mixture of 50% aqueous sulphuric acid (3 ml) and heptane (12 ml) at 130 °C. The heptane layer (2 ml) was removed after 1 h and stirred for 5 min with saturated aqueous sodium chloride (10 ml) and heptane (10 ml). The heptane layer was separated, dried ($MgSO_4$), and solvent removed on a rotatory evaporator to afford a pale yellow oil (0.7 ml). The sample was examined by n.m.r. and g.l.c./mass spectrometry. The remaining reaction mixture was continued for 48 h and by the same procedure gave an oil (1.1 ml). The methyl lavandulyl esters (**18**) and (**20**) and the γ- and δ-lactones [(**27**), (**28**), (**29**), and (**30**)] were separated by preparative g.l.c. (Table 1).

Rearrangement of Methyl trans-5-*Methyl*-2-*propen*-2-*ylhex*-3-*enoate* (**18**).—Compound (**18**) (150 μl) in hexane (0.3 ml) was stirred with 50% aqueous sulphuric acid (150 μl) at room temperature. Samples were removed and analysed according to the above procedure (Table 2).

Rearrangement of Methyl trans-5-*Methyl*-2-(2-*hydroxypropan*-2-*yl*)*hex*-3-*enoate* (**19**).—Compound (**19**) (250 μl) in hexane (0.6 ml) was stirred with 50% aqueous sulphuric acid (250 μl) at room temperature. Samples were removed and analysed according to the above procedure (Table 1).

Reaction of Methyl trans-*5-Methyl-2-propan-2-ylidenehex-3-enoate* (**20**).—Compound (**20**) (200 μl) in hexane (0.5 ml) was stirred with 50% aqueous sulphuric acid (200 μl) for 90 h at room temperature. Work-up and analysis of the oil by n.m.r. spectroscopy confirmed that it was starting material.

Deuteriation of trans-*Methyl Chrysanthemate* (**17**).—A mixture of *trans*-methyl chrysanthemate (2 ml) and 50% deuteriated sulphuric acid (2 ml) [D_2O (1 ml) and D_2SO_4 (1 ml)] in pentane (8 ml) were stirred at room temperature. Samples (0.5 ml) of the pentane mixture were removed after 145 and 356 h and the pentane removed by nitrogen. The methyl lavandulyl esters (**18**) and (**19**) as well as (**17**) were separated by preparative g.l.c. and n.m.r. spectra were taken in order to analyse the amount of deuterium exchange.

Deuteriation of Methyl trans-*5-Methyl-2-propen-2-ylhex-3-enoate* (**18**).—Compound (**18**) (0.14 ml) in hexane (0.3 ml) were stirred with deuteriated 50% sulphuric acid (0.14 ml) for 120 h at room temperature. Work-up gave an oil, the composition of which was determined from the intensities of the methyl esters in the n.m.r. spectrum.

Deuteriation of Methyl trans-*5-Methyl-2-(2-hydroxypropan-2-yl)hex-3-enoate* (**19**).—Compound (**19**) (0.4 ml) in hexane (1 ml) was stirred with 50% deuteriated sulphuric acid (0.4 ml) for 143 h. Work-up and analysis of the oil from the n.m.r. spectrum gave a mixture of lavandulyl esters.

Acidic Methanolysis of trans-*Methyl Chrysanthemate* (**17**).—A mixture of *trans*-methyl chrysanthemate (1 ml) and 50% methanolic sulphuric acid (1 ml) in pentane (4 ml) were stirred at room temperature for 93 h. Work-up gave an oil of composition: (**17**) 8%, (**18**) 16%, (**19**) 16%, (**22**) 19%, (**21**) 5%, (**20**) 33%, and (**26**) 3%. A mixture of (**17**) and 5% methanolic sulphuric acid (20 ml) was refluxed for 24 h. The mixture was cooled and extracted with ether, solvent was removed under reduced pressure from the extracts. The residual oil was stirred in pentane (25 ml) with a mixture of anhydrous magnesium sulphate and Nurite for 15 min. The mixture was filtered and solvent removed to afford a yellow oil of composition (**17**) 37%, (**18**) 7%, (**19**) 1%, (**21**) 1.5%, (**22**) 2%, (**26**) 44%, and unassigned esters 7.5%.

Methyl trans-*5-methyl-2-propen-2-ylhex-3-enoate* (**18**) (Found: C, 72.7; H, 10.1. Calc. for $C_{11}H_{18}O_2$: C, 72.49; H, 9.95%); $\nu_{max.}$(neat) 3 080 (CH=CH_2), 1 735 (CO), 1 645, 970 (*trans*-CH=CH), and 895 cm^{-1} (CH=CH_2); δ_H 5.58 (1 H, dd, *J* 16.0 and 7.0 Hz), 5.51 (1 H, dd, *J* 16.0 and 5.5 Hz), 4.89 (1 H, split s), 4.88 (1 H, split s), 3.70 (3 H, s), 3.64 (1 H, d, *J* 7.0 Hz), 2.33 (1 H, m), 1.75 (3 H, split s), and 1.00 (6 H, d, *J* 6.7 Hz); *m/z* 182 (M^+, 2.88%), 167 (2.66), 150 (1.76), 139 (14.6), 135 (2.36), 123 (75.5), 114 (14.47), 111 (2.51), 109 (6.06), 107 (23.19), 95 (16.77), 93 (16.6), 91 (20.65), and 81 (100).

Methyl trans-*5-methyl-2-(2-hydroxypropan-2-yl)hex-3-enoate* (**19**) (Found: C, 66.2; H, 10.05. Calc. for $C_{11}H_{20}O_3$: C, 65.97; H, 10.07%); $\nu_{max.}$(neat) 3 510 (OH) and 1 730 cm^{-1} (CO); δ_H 5.59 (1 H, dd, *J* 15.3 and 5.4 Hz), 5.52 (1 H, dd, *J* 15.3 and 7.3 Hz), 3.72 (3 H, s), 3.17 (1 H, bs, OH), 2.96 (1 H, d, *J* 7.3 Hz), 2.33 (1 H, m), 1.23 (3 H, s), 1.18 (3 H, s), 1.01 (3 H, d, *J* 6.7 Hz), and 0.99 (3 H, d, *J* 6.7 Hz); *m/z* 201 (M^+ + 1, 1.18%), 151 (2.72), 143 (5.57), 142 (59.71, $M^+ - Me_2CO$), 127 (82.27), 123 (11.19), 110 (12.28), 95 (58.55), 87 (37.51), and 59 (94.23).

Methyl trans-*5-methyl-2-propan-2-ylidenehex-3-enoate* (**20**) (Found: C, 72.2; H, 9.85. Calc. for $C_{11}H_{18}O_2$: C, 72.49; H, 9.95%); $\nu_{max.}$(neat) 1 725 (CO), 1 640, 1 615 (C=C), 1 078, 1 065, 955 (*trans*-CH=CH), 845 (C=CH), and 755 cm^{-1}; δ_H 6.20 (1 H, d, *J* 16.2 Hz), 5.47 (1 H, dd, *J* 16.2 and 6.7 Hz), 3.81 (3 H, s), 2.37 (1 H, m), 1.83 (3 H, s), 1.79 (3 H, s), and 1.02 (6 H, d, *J* 6.7 Hz); *m/z* 182 (M^+, 12.57%), 167 (4.99, $M - CH_3$), 151 (8.75, $M - CH_3OH$), 150 (14.86), 139 (88.85), 123 (19.85), 107 (76.72), 95 (21.29), 81 (51.59), 80 (37.68), 79 (100), 77 (27.39), 73 (30.88), 67 (39.34), and 59 (48.41).

trans-*5-Methyl-2-propan-2-ylidenehex-3-enoic acid* (**20a**), δ_H 12.36 (1 H, br s), 6.19 (1 H, d, *J* 16.2 Hz), 5.67 (1 H, dd, *J* 16.2 and 6.5 Hz), 2.40 (1 H, m), 1.95 (3 H, s), 1.88 (3 H, s), and 1.04 (6 H, d, *J* 7.0 Hz); *m/z* 168 (M^+, 13.19%), 153 (7.64), 138 (1.39), 126 (1.39), 125 (9.72), 124 (2.08), 123 (9.03), 107 (34.03), 95 (8.33), 91 (17.36), 81 (19.44), 79 (17.36), 77 (10.42), 73 (1.39), 69 (13.19), 67 (22.22), 65 (11.11), and 55 (12.5).

Methyl trans-*5-methylhex-3-enoate* (**21**), δ_H 5.54 (1 H, dd, *J* 15.6 and 5.1 Hz), 5.46 (1 H, dd, *J* 15.6 and 5.7 Hz), 3.69 (3 H, s), 3.03 (2 H, d, *J* 5.7 Hz), 2.28 (1 H, m), and 0.99 (6 H, d, *J* 6.9 Hz); *m/z* 142 (M^+, 8.52%), 110 (8.64), 87 (12.30), 85 (48.54), 83 (34.56), 82 (100), 74 (51.05), 69 (56.32), 68 (26.11), 67 (56.32), 59 (38.07), and 55 (83.51).

Methyl trans-*5-methyl-2-(2-methoxypropan-2-yl)hex-3-enoate* (**22**) (Found: C, 67.55; H, 10.5. Calc. for $C_{12}H_{22}O_3$: C, 67.26; H, 10.35%); $\nu_{max.}$(neat) 1 735 (CO), 1 075 (OCH_3), and 975 cm^{-1} (*trans*-CH=CH); δ_H 5.51 (1 H, dd, *J* 15.6 and 5.7 Hz), 5.49 (1 H, dd, *J* 15.6 and 5.4 Hz), 3.69 (3 H, s), 3.23 (3 H, s), 3.20 (1 H, d, *J* 5.4 Hz), 2.29 (1 H, m), 1.24 (3 H, s), 1.17 (3 H, s), 1.00 (3 H, d, *J* 6.7 Hz), and 0.97 (3 H, d, *J* 6.7 Hz); *m/z* 199 ($M^+ - CH_3$, 0.43%), 182 (0.48), 167 (1.01), 151 (0.56), 141 (2.09), 135 (0.28), 127 (2.58), 123 (3.92), 107 (2.04), 99 (6.04), and 73 (100).

Methyl cis-*5-methyl-2-propen-2-ylhex-2-enoate* (**23**), δ_H 6.81 (1 H, t, *J* 7.8 Hz), 5.16 (1 H, br s), 4.75 (1 H, br s), 3.75 (3 H, s), 2.30 (1 H, m), 2.11 (2 H, dd, *J* 7.8 and 6.9 Hz), 1.87 (3 H, s), and 0.92 (6 H, d, *J* 6.6 Hz).

Methyl trans-*5-methyl-2-propan-2-ylhex-2-enoate* (**24**), $\nu_{max.}$ (neat) 1 720 (CO), 1 640, 900, and 810 (CH=C); δ_H 5.73 (1 H, dt, *J* 7.5 Hz), 3.75 (3 H, s), 2.69 (1 H, m), 2.18 (2 H, dd, *J* 7.5 and 6.9 Hz), 1.67 (1 H, m), 1.06 (6 H, d, *J* 6.9 Hz), and 0.90 (6 H, d, *J* 6.6 Hz); *m/z* 184 (M^+, 38.46%), 169 ($M^+ - CH_3$, 21.37), 153 (12.82), 142 (8.55), 137 (62.39), 129 (27.35), 127 (46.15), 110 (17.95), 109 (37.61), 95 (70.09), 83 (86.32), 81 (31.62), 74 (54.7), and 69 (100).

Methyl trans-*5-methyl-2-propan-2-ylidenehexanoate* (**25**), δ_H 3.73 (3 H, s), 2.27 (2 H, m), 1.94 (3 H, s), 1.80 (3 H, s), 1.54 (1 H, m), 1.24 (2 H, m), and 0.90 (6 H, d, *J* 6.6 Hz); *m/z* 184 (M^+, 81.18%), 169 ($M^+ - CH_3$, 18.64), 153 (10.00), 141 (10.45), 137 (5.45), 129 (16.82), 115 (18.18), 109 (27.27), 96 (40.00), 95 (85.00), 83 (22.73), 73 (48.64), 69 (64.55), 68 (15.91), and 67 (100.00).

Methyl 2,2-*dimethyl*-3-(2-*methoxy*-2-*methylpropan*-2-*yl*)-*cyclopropanecarboxylate* (**26**) (Found: C, 67.55; H, 10.45. Calc. for $C_{12}H_{22}O_3$: C, 67.26; H, 10.35%); $\nu_{max.}$(neat) 2 820 (MeO), 1 725 (CO), 1 380, 1 365, 1 080 (MeO), 1 040, 965, 920, and 850 cm^{-1}; δ_H 3.67 (3 H, s), 3.20 (3 H, s), 1.61 (1 H, dd, *J* 14.1 and 6.6 Hz), 1.50 (1 H, dd, *J* 14.1 and 6.6 Hz), 1.41 (1 H, dt, *J* 6.6 and 6.0 Hz), 1.23 (3 H, s), 1.19 (1 H, d, *J* 6.0 Hz), 1.17 (6 H, s), and 1.13 (3 H, s); *m/z* 199 ($M^+ - CH_3$, 0.61%), 182 (0.56), 167 (1.26), 151 (0.66), 141 (2.87), 127 (2.95), 123 (4.14), 107 (2.06), 99 (6.46), 95 (2.71), 81 (2.23), 74 (4.29), 73 (100), and 67 (3.17).

5,6-*Dihydro*-6,6-*dimethyl*-3-*propan*-2-*yl*-2H-*pyran*-2-*one* (**27**), $\nu_{max.}$(neat) 1 720 (CO), 1 388, 1 372, 1 310, 1 270, 1 172, 1 105, 1 055, 950, 820, and 775 cm^{-1}; δ_H 6.42 (1 H, dt, *J* 4.5 and 1.3 Hz), 2.89 (1 H, m), 2.42 (2 H, d, *J* 4.5 Hz), 1.42 (6 H, s), and 1.10 (6 H, d, *J* 6.7 Hz); *m/z* 168 (M^+, 16.87%), 153 (38.36), 139 (4.66), 125 (10.60), 123 (12.63), 112 (5.70), 111 (7.05), 110 (28.09), 109 (8.84), 95 (54.29), 81 (23.47), 79 (8.27), 69 (8.60), 68 (8.15), 67 (53.64), and 56 (16.81).

3,5-*Di-isopropylfuran*-2(5H)-*one* (**28**), δ_H 6.60 (1 H, dd, *J* 1.6 and 1.3 Hz), 4.69 (1 H, dd, *J* 5.7 and 1.6 Hz), 2.68 (1 H, m), 1.96 (1

H, m), 1.18 (6 H, d, *J* 6.7 Hz), and 0.98 (6 H, d, *J* 7.0 Hz); *m/z* 168 (M^+, 18.20%), 153 (3.25), 140 (2.93), 125 (69.40), 112 (20.51), 107 (9.50), 97 (100), 85 (20.72), 83 (35.14), 73 (97.90), 71 (99.10), 70 (12.91), 69 (77.78), and 59 (100).

4,5-*Dihydro*-5-*propan*-2-*yl*-3-*propan*-2-*ylidenefuran*-2(3H)-*one* (**29**) (Found: C, 71.15; H, 90.45%. Calc. for $C_{10}H_{16}O_2$: C, 71.39; H, 9.58%), $\nu_{max.}$(neat) 1 745 (CO), 1 688 (C=C), 1 268, 1 195, 1 055, 1 015, 755, and 730 cm^{-1}; δ_H 4.12 (1 H, dt, *J* 7.8 and 6.7 Hz), 2.83 (1 H, dd, *J* 16.2 and 7.8 Hz), 2.51 (1 H, dd, *J* 16.2 and 6.7 Hz), 2.24 (3 H, split s), 1.85 (3 H, br s), 1.82 (1 H, m), 0.98 (3 H, d, *J* 6.7 Hz), and 0.91 (3 H, d, *J* 6.7 Hz); *m/z* 168 (M^+, 29.17%), 153 ($M - CH_3$, 3.16%), 140 ($M - CO$, 4.17%), 125 (82.33), 97 (100), 69 (61.06), 68 (33.48), and 67 (61.49).

4,5-*Dihydro*-5-*ethyl*-5-*methyl*-3-*propan*-2-*ylidenefuran*-2(3H)-*one* (**30**), δ_H 2.63 (2 H, ABq, *J* 16.2 Hz), 2.26 (3 H, split s), 1.85 (3 H, br s), 1.67 (2 H, q, *J* 7.3 Hz), 1.36 (3 H, s), and 0.94 (3 H, t, *J* 7.3 Hz); *m/z* 168 (M^+, 44.53%), 153 ($M^+ - CH_3$, 11.34%), 139 [$M - C_2H_5$, 41.7], 111 (8.50), 107 (16.19), 96 (21.05), 95 (15.79), 68 (100), 67 (92), and 57 (72.47).

Acknowledgements

We thank the Israel National Council for Research and Development for support and for a research fellowship (B. C.), the Royal Society of Chemistry Research Fund for an equipment grant, and Dr. S. Hoz for valuable suggestions and helpful discussions.

References

1 M. Elliott and N. F. Janes, in 'Pyrethrum—the Natural Insecticide,' ed. J. E. Casida, Academic Press, New York, 1973, p. 56.
2 W. W. Epstein and C. D. Poulter, *Phytochemistry*, 1973, **12**, 737; R. M. Coates, *Prog. Chem. Org. Nat. Products*, 1976, **33**, 73.
3 R. B. Bates and S. K. Paknikar, *Tetrahedron Lett.*, 1965, 1453; R. B. Bates and D. Feld, *Tetrahedron Lett.*, 1967, 4875.
4 L. Crombie, R. P. Houghton, and D. K. Woods, *Tetrahedron Lett.*, 1967, 4553.
5 L. Crombie, P. A. Firth, R. P. Houghton, D. A. Whiting, and D. K. Woods, *J. Chem. Soc., Perkin Trans. 1*, 1972, 642.
6 T. Takemoto and T. Nakajima, *Yakugaku Zasshi*, 1957, **77**, 1310.
7 W. J. Guilford and R. M. Coates, *J. Am. Chem. Soc.*, 1982, **104**, 3506.
8 C. H. De Puy, A. H. Andrist, and P. C. Funfshilling, *J. Am. Chem. Soc.*, 1974, **96**, 948; C. H. De Puy, *Fortschr. Chem. Forsch*, 1973, **40**, 73.
9 D. V. Banthorpe, S. Doonan, and J. A. Gutowski, *Phytochemistry*, 1977, **16**, 85.
10 D. A. Otieno, G. Pattenden, and C. R. Popplestone, *J. Chem. Soc., Perkin Trans. 1*, 1977, 196.
11 G. Ohloff, *Tetrahedron Lett.*, 1965, 3795.
12 J. Ficini and J. d'Angelo, *Tetrahedron Lett.*, 1976, 2441.
13 D. A. Otieno and G. Pattenden, *Pestic. Sci.*, 1980, **11**, 270.
14 I. Shirley, I. H. Smith, and D. A. Whiting, *Tetrahedron Lett.*, 1982, 1501; J. M. Biot, D. De Keukeleire, and M. Verzela, *Bull. Soc. Chim. Belg.*, 1977, **86**, 973; A. S. Kende and B. H. Todd, *J. Org. Chem.*, 1982, **47**, 163.
15 S. H. Harper and H. W. B. Reed, *J. Sci. Food Agric.*, 1951, 414.
16 C. Pascual, J. Meier, and W. Simon, *Helv. Chim. Acta*, 1966, **49**, 164; R. M. Silverstein, G. C. Bassler, and T. C. Morrill, 'Spectrometric Identification of Organic Compounds,' John Wiley and Sons, 1981, 4th edn., p. 227.
17 M. F. Ansell and M. H. Palmer, *J. Chem. Soc.*, 1963, 2640.
18 M. F. Ansell and M. H. Palmer, *Q. Rev. Chem. Soc.*, 1964, **18**, 211 (ref. 1*c*).
19 W. H. Saunders and A. F. Cockerill, 'Mechanisms of Elimination Reactions,' Wiley-Interscience, 1973.
20 H. G. Richey, Jr., 'Carbonium Ions,' eds. G. A. Olah and P. von R. Schleyer, Wiley-Interscience, 1972, vol. III, ch. 25; R. Breslow, in 'Molecular Rearrangements,' ed. P. de Mayo, Interscience, 1963, part 1, ch. 4; G. A. Olah, *Angew. Chem., Int. Ed. Engl.*, 1973, **3**, 173; M. Hanack and H. J. Schneider, *Angew. Chem., Int. Ed. Engl.*, 1967, **6**, 666.
21 K. M. Majerski and Z. Majerski, *Tetrahedron Lett.*, 1973, 4915.
22 S. Julia, M. Julia, and G. Linstrumelle, *Bull. Soc. Chim. Fr.*, 1966, **11**, 3499.
23 R. O. Clinton and S. C. Laskowski, *J. Am. Chem. Soc.*, 1948, **78**, 3135.
24 R. B. Woodward and R. Hoffmann, 'Conservation of Orbital Symmetry', Verlag Chemie, 1970, p.132.
25 G. Popják and J. W. Cornforth, *Biochem. J.*, 1966, **101**, 553.
26 E. E. van Tamelen and M. A. Schwartz, *J. Am. Chem. Soc.*, 1971, **93**, 1780.
27 A. F. Bramwell, L. Crombie, P. Hemsley, and G. Pattenden, *Tetrahedron*, 1969, **25**, 1727.

Received 31*st January* 1984; *Paper* 4/171