Thermolysis and Co^{II}-tetraphenylporphyrin-catalysed decomposition of substituted cycloheptatriene endoperoxides: a new synthetic approach to substituted dihydrooxepines

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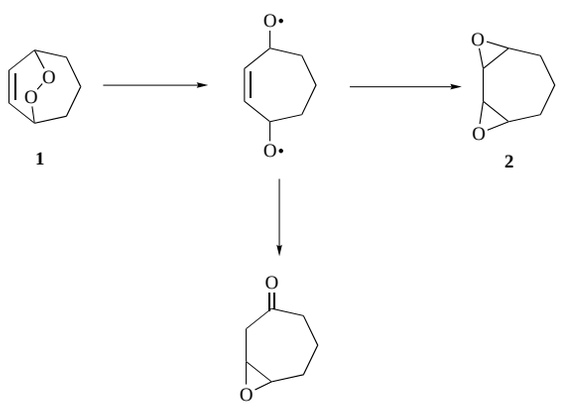
Photooxygenation of the carbonyl group-substituted cycloheptatrienes 14–17 affords the corresponding [2+4] cycloaddition products derived from cycloheptatriene and its valence isomer norcaradiene as well as rearranged aromatic compounds. Thermolysis of the cycloheptatriene endoperoxides 19, 22, 23, 26, 27 and 31 at 174 °C gives the corresponding bis-epoxides, no rearranged products being observed. However, treatment of 19, 26 and 31 with cobalt tetraphenylporphyrin provides the ring-opened products 47, 49 and 51 which are easily converted into the substituted 4,5-dihydrooxepine derivatives 48, 50 and 52. The outcome of Co-TPP-catalysed rearrangement is discussed in terms of different conformers.

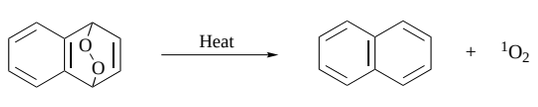
The reaction of 1,3-cyclic dienes with singlet oxygen is the most general and frequently used route to bicyclic endoperoxides. Thermolysis of unsaturated bicyclic endoperoxides gives *cis*-bis-epoxides and epoxy ketones[1] (Scheme 1). The formation of the



Scheme 1

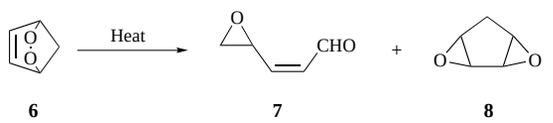
cis-epoxide **2** is readily rationalized in terms of homolytic fission of the peroxide bond in **1** to form a diradical, followed by intramolecular addition to the adjacent double bond.[1] Carless *et al.*[2] suggested that the 1,3-diradicals formed by closure of the first epoxide can rearrange by a hydrogen shift to an enol and ultimately tautomerize to the ketone **3**.

In cases where endoperoxides gain significant resonance stabilization, a carbon–oxygen bond can also be cleaved. Thus, certain arene endoperoxides when heated generate singlet oxygen and the corresponding aromatic compounds.[3]

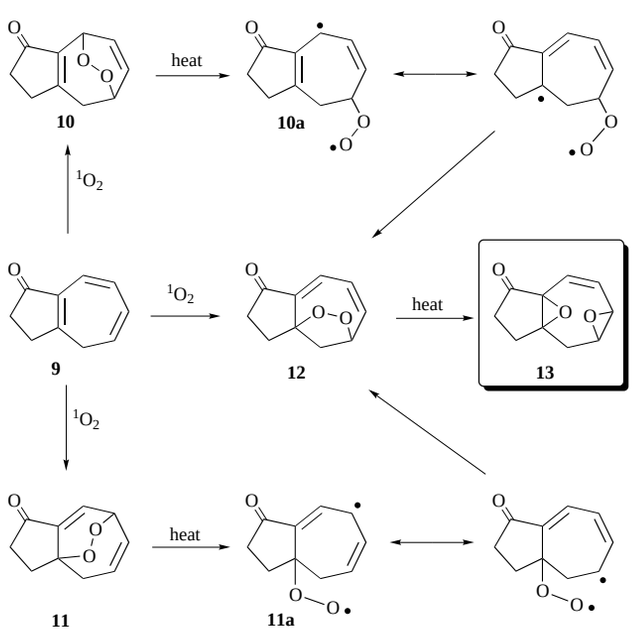


A third way for endoperoxide thermolysis to occur is by C–C cleavage; this is observed only in smaller ring systems. Thermolysis of 2,3-dioxabicyclo[2.2.1]hept-5-ene **6** occurs by a novel C–C bond cleavage not observed in its larger bicyclic homologues.[4]

Recently, we described an example of carbon–oxygen bond cleavage of endoperoxides at higher temperatures where aromatic systems cannot be formed.[5]



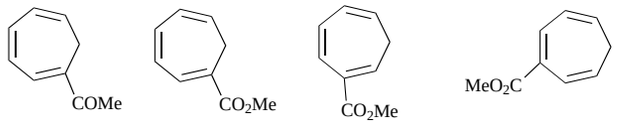
The endoperoxides **10**–**12** derived from the photooxygenation of **9** were subjected to thermolysis.[5] To our surprise the bis-epoxide **13** was formed from the thermolysis of all three endoperoxides **10**–**12** in addition to the expected bis-epoxides (Scheme 2). For the formation of bis-epoxide **13** we



Scheme 2

postulated the following reaction mechanism involving decomposition by two different pathways: (a) cleavage of the oxygen–oxygen bond which leads to the corresponding bis-epoxides by addition of the resulting oxygen radicals to an adjacent double bond and (b) cleavage of the carbon–oxygen bond as depicted in Scheme 2.

We assumed that the driving force for cleavage of carbon–oxygen bonds is the formation of the oxygen and carbon diradicals **10a** and **11a** which can be stabilized by the conjugated vinyl and carbonyl groups. In order to test the generality of this new endoperoxide–endoperoxide rearrangement we



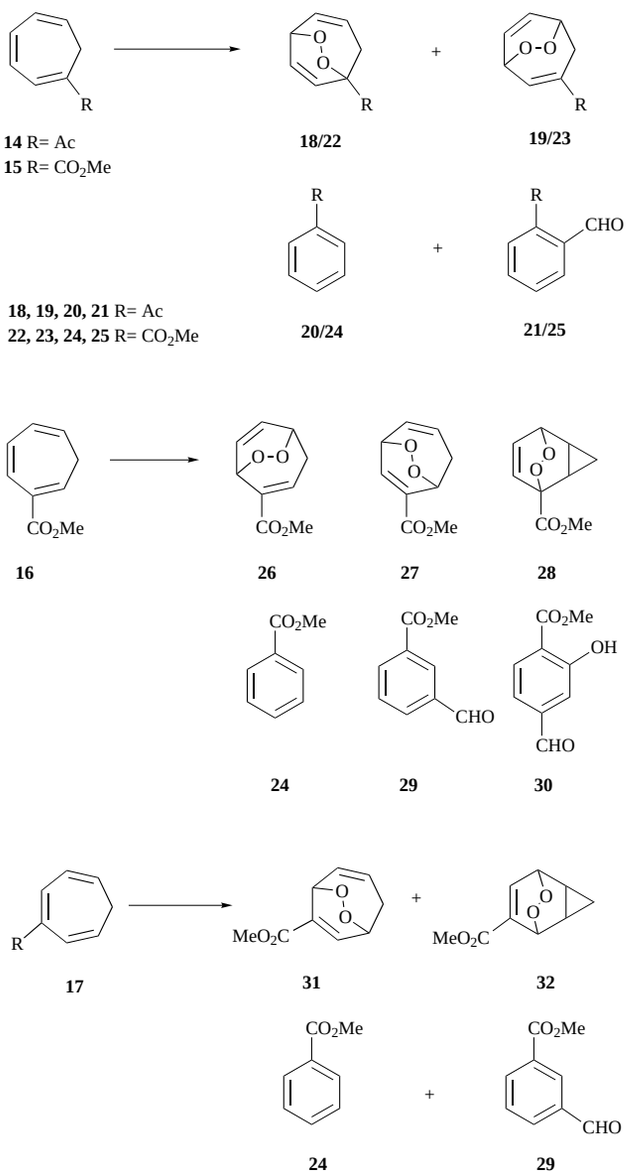
14 **15** **16** **17**

have synthesized seven cycloheptatriene endoperoxides derived from carbonyl group-substituted cycloheptatrienes **14**–**17** and investigated their thermolysis reactions.

Furthermore, we were also interested in CoTPP-catalysed decomposition of the endoperoxides formed in view of the synthesis of substituted 4,5-dihydrooxepine derivatives which are subunits of many biologically active compounds.[6]

Results and discussion

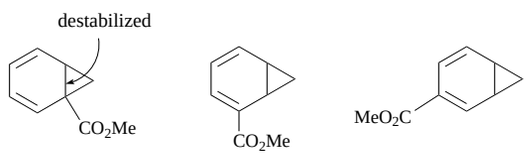
We first investigated the photooxygenation of the substituted cycloheptatrienes **14**–**17** in CCl_4 at 10 °C with tetraphenylporphyrin (TPP) as a sensitizer (Scheme 3). In our early work



Scheme 3

we showed that singlet oxygen can add to cycloheptatriene and its derivatives to form [2+4] adducts derived from cycloheptatriene and its valence isomer norcaradiene.[7] ^{1}H NMR Spectra of the crude materials showed that the endoperoxides were formed in addition to aromatic aldehydes. Careful silica gel chromatography of the mixture formed after photooxygenation of **14** and **15** provided two bicyclic endoperoxides **18**/**19** and **22**/**23**, methyl benzoate (acetophenone) and some aromatic aldehydes **21**/**25**. In contrast, photooxygenation of **16** and **17** formed norcaradiene endoperoxides **28** and **32**, respectively, as well as the expected cycloheptatriene endoperoxides **26**, **27** and **31**. The ^{1}H and ^{13}C NMR spectra have been definitive in assigning the proposed structures of the endoperoxides after using double resonance and NOE experiments.

It has already been shown that π-acceptor substituents (CN, CHO, COMe and CO_2Me, can stabilize the norcaradiene structure by strengthening the distal cyclopropane bond.[8] In contrast, these substituents also destabilize the vicinal bonds in cyclopropane which is initially formed at an early stage in the cycloheptatriene–norcaradiene rearrangement so that system **33** reverts to cycloheptatriene. In the case of 2- and 3-substituted cycloheptatrienes, however, the destabilizing effect of the carbonyl group on the formation of the norcaradiene isomers **34** and **35** is absent. Because of this, only **16** and **17** can provide norcaradiene adducts which is in agreement with experimental results.



33 **34** **35**

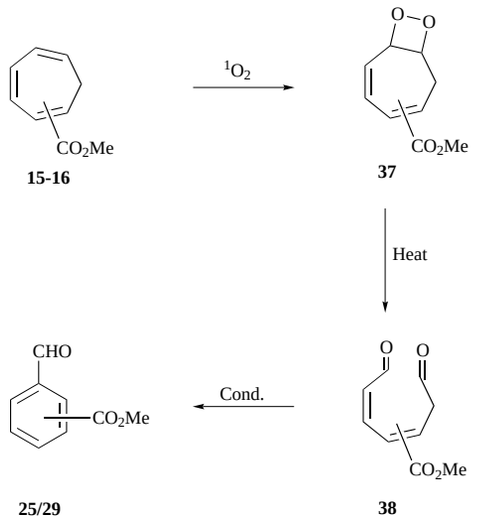
Since the cycloheptatrienes **14**–**17** have no symmetry, singlet oxygen can add to two different diene units. For compounds **14**–**16** we isolated two isomeric cycloheptatriene adducts although **17** provided only one, **31**, the second isomer **36** not being formed. In order to rationalize this outcome we have carried out AM1 calculations.[9]

The optimized geometries of isomers **31** and **36** (Fig. 1) were calculated by the AM1 method. Results from AM1 calculations (Table 1) show that the isomer **31** has a 12.5 kcal mol^{-1} lower heat of formation (−54.03 kcal mol^{-1}) than the unformed isomer **36** (−41.55 kcal mol^{-1}). The large energy gap between the two possible isomers indicates that the more thermodynamically stable isomer was formed by photooxygenation.

For the formation of the aromatic aldehydes, the dioxetanes are proposed as precursors. Low-temperature studies[10] have revealed that a 1,2-dioxetane is the precursor for the formation of benzaldehyde by photooxygenation of cycloheptatriene, while dioxetanes can easily undergo thermal cleavage to give dialdehydes. Since the methylene protons in **38** are activated by both a carbonyl group and double bond, **38** can readily undergo condensation to give substituted aromatic aldehydes (Scheme 4).

The next phase of this investigation was to probe the response of isolated bicyclic endoperoxides (**18**, **19**, **22**, **23**, **26**, **27**, **31**) to thermolysis. For this purpose, the endoperoxides dissolved in toluene were pyrolysed at 174 °C in a sealed tube. The thermal stability of endoperoxides is quite high and in all cases the corresponding bis-epoxides were the only products (Scheme 5). In the case of the acetyl compound **18** no product could be isolated, behaviour which can be attributed to the existence of carbonyl group activated methyl protons which can easily be attacked by oxygen radicals to cause ultimately the polymerization.

Careful examination of the thermolysis products failed to reveal any sign either of epoxy ketone formation or other rearranged products. This behaviour seems to be best explained by the fact that the carbonyl group has no effect on the outcome of the reaction as in cases **10**–**12**. This is because substituents such as COMe and CO_2Me have free rotation, whereas, for the stabilization of any radical intermediates like **10a** or **11a** it is



Scheme 4

very important that the carbonyl group has a rigid conformation, as in **9**, in order to achieve a maximum conjugation with the radical species formed. On the basis of this observation, we postulate that the geometry of the carbonyl group plays an important role by promoting carbon–oxygen cleavage in bicyclic endoperoxides.

Next, we turned our attention to the CoTPP-catalysed rearrangement of these endoperoxides. A wide variety of metal-induced decompositions of endoperoxides, by different reaction mechanisms, has been examined.[11] Foote *et al.*[12] reported that cobalt *meso*-tetraphenylporphyrin (CoTPP) promoted catalytic rearrangement of endoperoxides to bis-epoxides. We successfully applied this reaction to unsaturated bicyclic endoperoxides

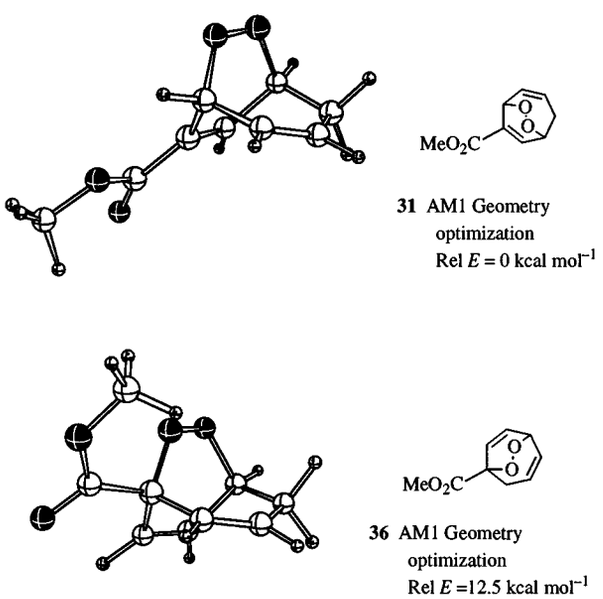
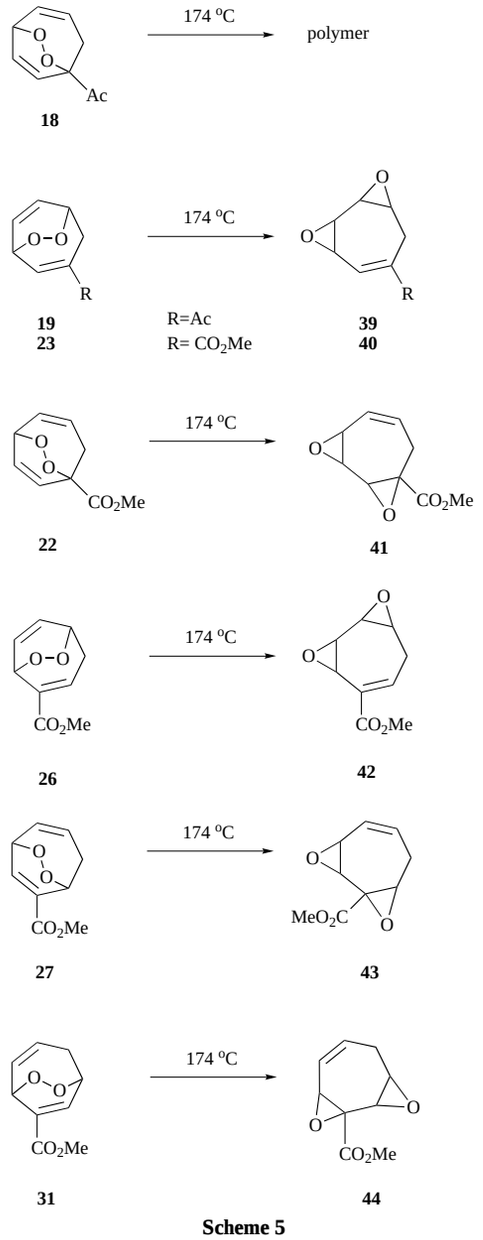


Fig. 1 Optimized geometries for the two isomers **31** and **36**

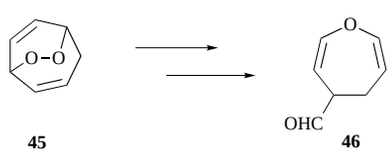
Table 1 Results from AM1 calculations

Substrate	ΔH_f/kcal mol^{-1}
18	1.147
19	−7.975
22	−45.756
23	−47.08
26	−54.97
27	−54.15
31	−54.03
36	−41.55

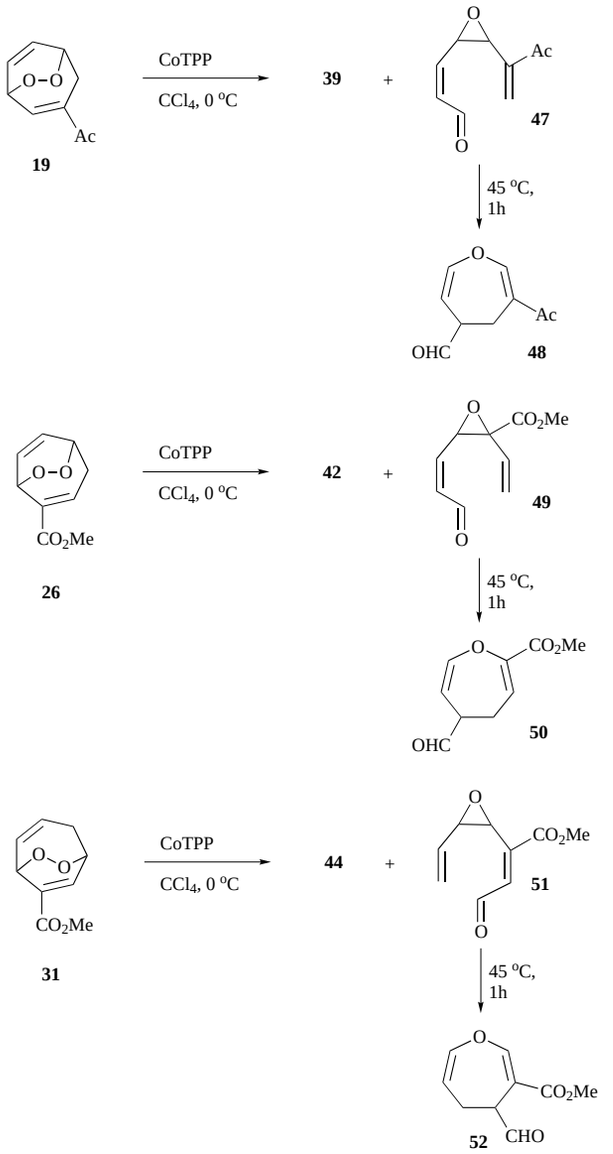


Scheme 5

with strained and perturbed diene moieties and found that CoTPP-catalysed reactions suppress the side reactions such as formation of epoxy ketones.[13] However, the reaction of cycloheptatriene [2+4] endoperoxide **45** with Co-TPP provided ring-opened aldehydes which could be easily converted into the 4,5-dihydrooxepine derivative **46**.



After discovery of the oxepine nucleus in a number of biologically active natural products, considerable attention has been focused on the construction of medium-sized ring ethers containing these substructures.[6,14] A small number of ingenious routes to these ethers have been described. One potentially attractive approach is the Cope rearrangement of divinyl epoxides, which leads to 4,5-dihydroxepines through four-carbon ring expansion of the epoxide.[13,15] CoTPP-catalysed decomposition of the endoperoxides derived from substituted cycloheptatrienes provides a useful route to unsymmetrically substituted 4,5-dihydrooxepine derivatives.



Scheme 6

The reaction of the endoperoxides **22**, **23** and **27** with a catalytic amount of CoTPP (at 0 °C) resulted mainly in the formation of the corresponding bis-epoxides **41**, **40** and **43** with endoperoxide **18** undergoing polymerization as in the case of the thermolysis. However, the endoperoxides **19**, **26** and **31** afforded divinyl epoxides **47**, **49** and **51** in yields of 20–30%. All compounds have been characterized by their ^{1}H and ^{13}C NMR spectral data. Unequivocal configurational evidence, especially at the epoxide ring, was made by means of chemical reactions. The isolated open-chain aldehydes **47**, **49** and **51** contain 1,2-divinyl ethylene oxide units that are suitable species for the Cope rearrangement. Therefore, the key step to convert the divinyl epoxides **47**, **49** and **51** into the corresponding dihydrooxepine derivatives **48**, **50** and **52** was [3.3] sigmatropic rearrangement which was easily completed in 1 h at 45 °C. On the basis of this reaction a *cis*-configuration at the epoxide ring was established. The ^{1}H and ^{13}C NMR spectra of the formed substituted dihydroxepines **48**, **50** and **52** exhibited the characteristic resonances of H-5 protons resonating at higher field than the other olefinic protons. Other resonances were also in agreement with the proposed structures.

In our early work,[14] we suggested a one-electron radical process for the decomposition mechanism which has been supported by the observation of β-cleavage during the CoTPP-catalysed decompositions of endoperoxides. We assume that conformational factors in the seven-membered ring, formed after cleavage of the oxygen–oxygen bond in the endoperoxides by an electron transfer mechanism, play an important role in determining the product distribution. The intermediates formed by cleavage of the peroxide linkage can adopt different conformations as shown in Fig. 2. The nearly parallel arrangement of the C–O bonds with the adjacent p orbital lobes is necessary for epoxide formation. If the intermediates can adopt the second conformation which has higher energy than the first one, a synchronous cleavage of the ring C–C bond can take place. This conformation holds the correct alignment of the C–O bond and p orbital for the formation of the epoxide ring. We assume that substituents are responsible for the formation of different conformers which would determine the product distribution.

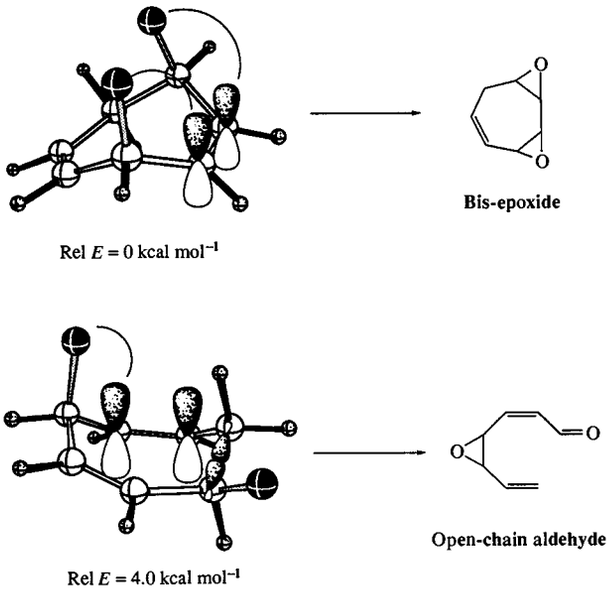


Fig. 2 Two stable conformers derived from cleavage of the cycloheptatriene endoperoxide **45** and their MM2 relative energies

In summary, we have synthesized seven different substituted cycloheptatriene endoperoxides and thermolysed each. In each case we isolated only the corresponding bis-epoxides, there being no indication of ring cleavage or the preferred carbon–oxygen cleavage as observed for **10**–**12**. We assume that ester or acetyl carbonyl groups bonded to a cycloheptatriene system exert no stabilizing effects on the radicals which may be formed upon carbon–oxygen bond cleavage. The rigid geometry of the carbonyl group is most likely required to promote carbon–oxygen cleavage. Furthermore, we have developed an efficient 3–4 step synthesis of 4,5-dihydrooxepines that features the Cope rearrangement of *cis*-1,2-divinyl epoxides. This method provides sufficient flexibility to allow the incorporation of a variety of substituents into 4,5-dihydrooxepine rings by utilization of various cycloheptatrienes.

Experimental

General details

Mps were determined on a Thomas-Hoover capillary melting point apparatus. IR spectra were obtained from films on NaCl plates for liquid or KBr pellets for solids on a Perkin-Elmer 337 IR recording spectrometer. ^{1}H and ^{13}C NMR spectra were recorded on 200 (50 MHz) Varian spectrometers, and are reported in δ units with $SiMe_4$ as internal standard. All column chromatography was performed on silica gel (60 mesh, Merck).

The substituted cycloheptatrienes **14**–**17** were synthesized as reported in the literature.

1-Acetylcyclohepta-1,3,5-triene 14[16]

δ_H(200 MHz, $CDCl_3$, Me_4Si) 7.06 (1 H, d, *J* 5.9, 2-H), 6.7 (1 H, dd, A-part of AB-system, *J* 11.0 and 5.5, 4-H), 6.7

(1 H, dd, B-part of AB-system, *J* 11.0 and 5.9, 3-H), 6.21 (1 H, dd, A-part of AB-system, *J* 9.4 and 5.4, 5-H), 5.5 (1 H, dt, B-part of AB-system, *J* 9.4 and 7.0, 6-H), 2.3 (1 H, d, *J* 7.0, 7-H) and 2.1 (3 H, s, $COCH_3$); δ_C(50 MHz, $CDCl_3$, Me_4Si) 197.21, 136.14, 133.15, 132.26, 129.38, 127.82, 126.52, 26.39 and 25.82.

Methyl cyclohepta-1,3,5-triene-1-carboxylate 15

δ_H(200 MHz, $CDCl_3$, Me_4Si) 7.18 (1 H, d, *J* 5.9, 2-H), 6.70 (1 H, dd, A-part of AB-system, *J* 11.0 and 5.4, 4-H), 6.58 (1 H, dd, B-part of AB-system, *J* 11.0 and 5.9, 3-H), 6.2 (1 H, dd, A-part of AB-system, *J* 9.4 and 5.4, 5-H), 5.5 (1 H, dt, B-part of AB-system, *J* 9.4 and 7.0, H-6), 3.75 (3H, s, OCH_3) and 2.6 (1 H, d, *J* 7.0, 7-H); δ_C(50 MHz, $CDCl_3$, Me_4Si) 167.24, 135.21, 133.45, 129.16, 127.08, 124.52, 122.26, 52.32 and 27.16.

Methyl cyclohepta-1,3,5-triene-2-carboxylate 16[17]

δ_H(200 MHz, $CDCl_3$, Me_4Si) 7.17 (1 H, d, A-part of AB-system, *J* 11.2, 3-H), 6.74 (1 H, dd, B-part of AB-system, *J* 11.2 and 5.5, 4-H), 6.50 (1 H, t, *J* 7.2, 1-H), 6.22 (1 H, dd, A-part of AB-system, *J* 9.5 and 5.5, 5-H), 5.35 (1 H, dt, B-part of AB-system, *J* 9.5 and 7.1, 6-C), 3.73 (3 H, s, OCH_3) and 2.3 (1 H, t, *J* 7.1, 7-C); δ_C(50 MHz, $CDCl_3$, Me_4Si) 167.22, 132.52, 130.38, 130.02, 128.65, 128.06, 121.24, 52.33 and 28.18.

Methyl cyclohepta-1,3,5-triene-3-carboxylate 17[17]

δ_H(200 MHz, $CDCl_3$, Me_4Si) 7.55 (1 H, d, *J* 5.8, 4-H), (1 H, d, A-part of AB-system, *J* 9.4, 2-H), 6.34 (1 H, dd, A-part of AB-system, *J* 9.6 and 5.8, 5-H), 6.66 (1 H, dt, B-part of AB-system, *J* 9.6 and 7.0, 6-H), 6.43 (1 H, dt, B-part of AB-system, *J* 9.4 and 7.1, 1-H), 3.80 (3H, s, OCH_3) and 2.26 (1 H, t, *J* 7.1, 7-H); δ_C(50 MHz, $CDCl_3$, Me_4Si) 168.22, 137.13, 133.64, 127.32, 126.41, 126.02, 121.23, 53.36 and 28.27.

General procedure for the photooxygenation of the substituted cyclohepta-1,3,5-trienes 14–17

A CCl_4 solution (250 cm^3) of each of the substituted cycloheptatrienes **14**–**17** (5–10 g) and tetraphenylporphyrin (50 mg) was irradiated with a projector lamp (150 W) while a slow stream of dry oxygen was passed through it continuously. The progress of the photooxygenation was monitored by ^{1}H NMR spectroscopy until essentially complete consumption of the starting material (12–48 h). The solvent was roto-evaporated at room temperature. Chromatography of the crude products on silica gel (80–110 g) with ethyl acetate–light petroleum (bp 40–65 °C) (1:9) as the eluent yielded the bicyclic endoperoxides and aromatic compounds.

Photooxygenation of 14

This compound (3.5 g, 23 mmol) was treated as described above to give the following compounds: (1) compound **20** (400 mg, 13%), (2) compound **21** (510 mg, 14.7%), (3) compound **19** (450 mg, 11.7%, pale yellow oil) and (4) compound **18** (230 mg, 6%, colourless oil).

3-Acetyl-6,7-dioxabicyclo[3.2.2]nona-2,8-diene 19. δ_H(200 MHz, $CDCl_3$, Me_4Si) 7.09 (1 H, dd, *J* 7.1 and 1.8, 2-H), 6.67 (1 H, br d, 8-H), 6.39 (1 H, br d, 9-H), 4.85 (2 H, m, 1-C and 5-C), 2.95 (1 H, ddd, A-part of AB-system, *J* 19.5, 5.0 and 1.8, 4-H), 2.62 (1 H, dt, B-part of AB-system, *J* 19.5 and 6, 4-H) and 2.3 (3 H, s, CH_3); δ_C(50 MHz, $CDCl_3$, Me_4Si) 198.24, 141.21, 139.64, 132.49, 128.53, 75.62, 72.74 and 34.22; ν_{max}(NaCl)/cm^{-1} 2970, 1705, 1430 and 1260 (Found: C, 65.3; H, 6.2. $C_9H_{10}O_3$ requires C, 65.05; H, 6.1%).

1-Acetyl-6,7-dioxabicyclo[3.2.2]nona-3,8-diene 18. δ_H(200 MHz, $CDCl_3$, Me_4Si) 6.67 (1-H, dd, *J* 9.4 and 7.0, 9-H), 6.38 (1 H, d, *J* 9.4, 8-H), 6.05 (1 H, ddt, 4-C), 5.65 (1 H, dt, 3-H), 4.67 (t, *J* 7.0, 5-H), 2.7 (1 H, ddd, A-part of AB-system, *J* 19.0, 4.1 and 2.0, 2-H), 2.62 (1 H, ddd, B-part of AB-system, *J* 19.0, 4.0 and 2.1, 2-H) and 2.4 (3 H, s, $COCH_3$); δ_C(50 MHz, $CDCl_3$, Me_4Si) 185.93, 136.14, 130.87, 127.32, 125.26, 87.21, 73.44, 38.22 and 25.94; ν_{max}(NaCl)/cm^{-1} 3040, 3000, 2970, 1750, 1450, 1280, 1430 and 1260 (Found: C, 65.4; H, 6.0. $C_9H_{10}O_3$ requires C, 65.05; H, 6.1%).

Photooxygenation of 15

This compound (5.0 g, 33 mmol) was treated as described above to give the following compounds: (1) compound **24** (700 mg, 13%), (2) compound **25** (230 mg, 5.5%), (3) compound **23** (760 mg, 11.1%, pale yellow crystals mp 57–58 °C from diethyl ether–hexane) and (4) compound **22** (450 mg, 8.3%, colourless oil).

Methyl 6,7-dioxabicyclo[3.2.2]nona-2,8-diene-3-carboxylate 23. δ_H(200 MHz, $CDCl_3$, Me_4Si) 7.23 (1 H, dt, *J* 7.0 and 2.0, 2-H), 6.70 (1 H, t, 8-H), 6.42 (1 H, t, 9-H), 4.85 (2 H, m, 1-H and 5-H), 3.73 (3 H, s, CO_2Me), 3.18 (1 H, ddd, A-part of AB-system, *J* 19.5, 5.0 and 2.1, 4-H) and 2.69 (1 H, dt, B-part of AB-system, *J* 19.5, 2.1, 4-C); δ_C(50 MHz, $CDCl_3$, Me_4Si) 167.62, 139.14, 135.57, 133.02, 127.84, 75.54, 72.55, 52.43 and 35.51; ν_{max}(NaCl)/cm^{-1} 3040, 3000, 2970, 1705, 1430 and 1260 (Found: C, 59.7; H, 5.7. $C_9H_{10}O_4$ requires C, 59.3; H, 5.5%).

Methyl 6,7-dioxabicyclo[3.2.2]nona-3,8-diene-1-carboxylate 22. δ_H(200 MHz, $CDCl_3$, Me_4Si) 6.85 (1 H, dd, *J* 9.4 and 7.0, 9-H), 6.45 (1 H, d, *J* 9.4, 8-H), 6.10 (1 H, ddt, 4-H), 5.70 (1 H, dt, 3-H), 4.70 (1 H, t, *J* 7.0, 5-H), 3.8 (3 H, s, CO_2Me), 3.0 (1 H, ddd, A-part of AB-system, *J* 19.0, 4.1 and 2.0, 2-H) and 2.60 (1 H, ddd, B-part of AB-system, *J* 19.0, 3.9 and 2.1, 2-H); δ_C(50 MHz, $CDCl_3$, Me_4Si) 169.87, 135.53, 130.52, 127.24, 124.86, 82.12, 74.52, 53.67 and 39.22; ν_{max}(NaCl)/cm^{-1} 3040, 3000, 2970, 1705, 1425, 1275, 1420 and 1250 (Found: C, 59.5; H, 5.55. $C_9H_{10}O_4$ requires C, 59.3; H, 5.5%).

Photooxygenation of 16

This compound (10.0 g, 67 mmol) was treated as described above. After completion of the reaction, the resulting mixture was heated at 70 °C for 1 h in order to transform **28** into the corresponding norcaradiene bis-epoxide **53** which can be easily separated.

The following compounds were isolated: (1) Compound **24** (1300 mg, 14.3%), (2) compound **26** (1200 mg, 10.0%, colourless liquid), (3) compound **27** (1400 mg, 11.7%, colourless liquid), (4) compound **29** (800 mg, 7.4%, colourless oil), (5) compound **30** (610 mg, 5.1%, colourless oil) and (6) compound **53** (900 mg, 7.5%, colourless oil).

Methyl 6,7-dioxabicyclo[3.2.2]nona-2,8-diene-2-carboxylate 26. δ_H(200 MHz, $CDCl_3$, Me_4Si) 6.94 (1 H, m, 3-H), 6.77 (1 H, ddd, A-part of AB-system, *J* 10.2, 7.5 and 1.3, 8-H), 6.41 (1 H, ddd, B-part of AB-system, *J* 10.2, 7.4 and 1.2, 9-H), 5.50 (1 H, d, *J* 7.5, 1-H), 4.80 (1 H, m, 5-H), 3.79 (3 H, s, CO_2Me), 3.10 (1 H, ddd, A-part of AB-system, *J* 20.6, 4.8 and 4.1, 2-H) and 2.55 (1 H, ddd, B-part of AB-system, *J* 20.6, 4.0 and 2.1, 2-C); δ_C(50 MHz, $CDCl_3$, Me_4Si) 166.23, 142.21, 134.51, 134.89, 126.72, 75.11, 73.22, 52.74 and 36.13; ν_{max}(NaCl)/cm^{-1} 3040, 3000, 2970, 1705, 1430 and 1260 (Found: C, 59.0; H, 5.3. $C_9H_{10}O_4$ requires C, 59.3; H, 5.5%).

Methyl 6,7-dioxabicyclo[3.2.2]nona-2,8-diene-2-carboxylate 27. δ_H(200 MHz, $CDCl_3$, Me_4Si) 7.63 (1 H, d, 8-H), 6.1 (1 H, m, 2-H), 5.71 (1 H, m, 3-H), 5.32 (1 H, m, 5-H), 4.82 (1 H, t, 1-H), 3.80 (3 H, s, CO_2Me), 2.94 (1 H, dddd, A-part of AB-system, 2-H) and 2.42 (1 H, ddd, B-part of AB-system 2-H); δ_C(50 MHz, $CDCl_3$, Me_4Si) 164.56, 142.21, 132.84, 129.65, 128.11, 75.44, 73.08, 52.66 and 35.83; ν_{max}(NaCl)/cm^{-1} 3040, 3000, 2970, 1705, 1430 and 1260 (Found: C, 59.6; H, 5.8. $C_9H_{10}O_4$ requires C, 59.3; H, 5.5%).

3-Hydroxy-4-methoxycarbonylbenzaldehyde 30. δ_H(200 MHz, $CDCl_3$, Me_4Si) 10.9 (1 H, s, OH), 10.0 (1 H, s, CHO), 8.05 (1 H, d, *J* 8.1, 5-H), 7.43 (1 H, dd, *J* 8.1 and 1.46, 6-H), 7.41 (1 H, d, *J* 1.46, 2-H) and 3.98 (3 H, s, CO_2Me); δ_C(50 MHz, $CDCl_3$, Me_4Si) 192.12, 170.12, 162.12, 143.43, 131.27, 121.24, 120.12, 119.26 and 52.39.

(1β,2α,4α,5α,7α,8β)-Methyl 3,6-dioxatetracyclo[6.1.0.0^{2,4}.0^{5,7}]nonane-2-carboxylate 53. δ_H(200 MHz, $CDCl_3$, Me_4Si) 3.77

(3 H, s, CO_2Me), 3.60 (1 H, br s, 4-H), 3.24 (2 H, br s, 5-H and 7-H), 1.54 (2 H, m, 1-H and 8-H), 1.18 (1 H, dt, 9-H) and 0.62 (1 H, q, 9-H); δ_C(50 MHz, $CDCl_3$, Me_4Si) 164.61, 56.12, 55.33, 54.81, 53.35, 50.16, 48.34, 11.58, 11.52 and 8.22; ν_{max}(NaCl)/cm^{-1} 3040, 3010, 1710, 1430, 1270 and 1210 (Found: C, 59.2; H, 5.45. $C_9H_{10}O_4$ requires C, 59.3; H, 5.5%).

Photooxygenation of 17

This compound (10.0 g, 67 mmol) was treated as described above. After completion of the reaction, the resulting mixture was heated at 70 °C for 1 h in order to transform **32** to the corresponding **54** which was easily separated.

The following compounds were isolated: (1) Compound **24** (1650 mg, 18.2%), (2) compound **29** (1.500 mg, 13.8%, colourless liquid), (3) compound **31** (1240 mg, 10.3%, colourless liquid) and (4) compound **54** (1400 mg, 11.7%, colourless crystals, mp 68–70 °C from diethyl ether–hexane).

Methyl 6,7-dioxabicyclo[3.2.2]nona-2,8-diene-8-carboxylate 31. δ_H(200 MHz, $CDCl_3$) 7.23 (dd, *J* 7.1, 1.5, H-C_9), 6.10 (ddt, A-part of AB-system, *J* 10.6, 7.1, 2.1, H-C_2), 5.72 (m, B-part of AB-system, H-C_3), 5.25 (dq, H-C_1), 4.96 (ddt, *J* 7.4, 5.3, 1.6, H-C_5), 3.80 (s, CH_3), 2.9 (dddd, A-part of AB-system, *J* 19.5, 5.6, 3.6, 2.1, H-C_4) and 2.35 (ddt, B-part of AB-system, *J* 19.5, 3.6, 1.8, H-$C_{4'}$); δ_C(50 MHz, $CDCl_3$, Me_4Si) 164.53, 138.76, 133.71, 131.62, 128.74, 75.33, 73.12, 52.73 and 35.46; ν_{max}(NaCl)/cm^{-1} 3030, 3000, 2960, 1740, 1440 and 1270 (Found: C, 59.05; H, 5.2. $C_9H_{10}O_4$ requires C, 59.3; H, 5.5%).

(1β,2α,4α,5α,7α,8β)-Methyl 3,6-dioxatetracyclo[6.1.0.0^{2,4}.0^{5,7}]nonane-4-carboxylate 54. δ_H(200 MHz, $CDCl_3$, Me_4Si) 3.91 (1 H, d, 2-H), 3.80 (3 H, s, CO_2Me), 3.58 (1 H, br s, 5-H), 3.36 (1 H, d, 7-H), 1.65 (2 H, m, 1-H and 8-H), 1.10 (1 H, dt, 9-H) and 0.55 (1 H, q, 9-H); δ_C(50 MHz, $CDCl_3$, Me_4Si) 165.23, 56.45, 53.42, 52.38, 50.27, 47.73, 12.31, 11.66 and 8.47; ν_{max}(KBr)/cm^{-1} 300, 3010, 1710 and 1210 (Found: C, 59.45; H, 5.15. $C_9H_{10}O_4$ requires C, 59.3; H, 5.5%).

Thermolysis of the endoperoxides: 18, 19, 22, 23, 26, 27 and 31

A solution of each of the endoperoxides (500 mg, 2.7 mmol) in toluene (5 ml) sealed *in vacuo* in a constricted test tube was heated in an oil-bath for 14 h. After cooling to room temperature, the mixture was roto-evaporated and the residue analysed by ^{1}H NMR spectroscopy to assure complete transformation of the endoperoxide. The thermolysate was submitted to silica gel chromatography with ethyl acetate–hexane (1:4) as eluent. Structural identification was established on the basis of spectral and elemental analysis.

(1α,2α,4α,8α)-6-Acetyl-3,9-dioxatricyclo[8.1.0.0^{2,4}]non-6-ene 39. A colourless oil (425 mg, 85%); δ_H(200 MHz, $CDCl_3$, Me_4Si) 6.79 (1 H, dd, *J* 2.4 and 1.6, 7-H), 3.70 (1 H, dd, A-part of AB-system, *J* 3.9 and 2.4, 8-H), 3.65 (1 H, t, B-part of AB-system, *J* 3.9, 1-H), 3.4–3.1 (2 H, m, 2-H and 4-H), 3.04 (dt, A-part of AB-system, *J* 13.8, 5-H), 2.85 (1 H, ddd, B-part of AB-system, *J* 13.8, 6.5 and 1.6, 5-H), 2.60 (3 H, s, COMe); δ_C(50 MHz, $CDCl_3$, Me_4Si) 198.26, 142.27, 134.13, 53.22, 52.85, 50.17, 48.94, 26.32 and 25.47; ν_{max}(NaCl)/cm^{-1} 2995, 2910, 1670, 1450 and 1250 (Found: C, 65.3; H, 6.2. $C_9H_{10}O_3$ requires C, 65.05; H, 6.1%).

Methyl (1α,2α,4α,8α)-3,9-dioxatricyclo[8.1.0.0^{2,4}]non-6-ene-6-carboxylate 40. Product (215 mg, 43%) had mp 57–58 °C; δ_H(200 MHz, $CDCl_3$, Me_4Si) 6.9 (1 H, br d, 7-H), 3.90 (3 H, s, CO_2Me) and 2.8–3.0 (6 H, m, epoxide-H and methylene-H); δ_C(50 MHz, $CDCl_3$, Me_4Si) 166.18, 135.23, 133.42, 53.86, 52.94, 52.87, 49.78, 48.93 and 24.66; ν_{max}(NaCl)/cm^{-1} 2990, 1690, 1450 and 1260 (Found: C, 59.4; H, 5.65. $C_9H_{10}O_4$ requires C, 59.3; H, 5.5%).

Methyl (1α,2α,4α,8α)-3,9-dioxatricyclo[6.1.0.0^{2,4}]non-6-ene-4-carboxylate 41. Product (266 mg, 54%) had mp 34–36 °C; δ_H(200 MHz, $CDCl_3$, Me_4Si) 5.96 (1 H, dt, A-part of AB-system, *J* 10.3 and 6.9, 6-H), 5.70 (1 H, ddd, B-part of AB-system, *J* 10.3, 4.0 and 1.8, 7-H), 3.75 (3 H, s, CO_2Me), 3.45–3.7 (2 H, m, 1-H, 2-H and 3-H), 2.94 (1 H, ddd, A-part of AB-system, *J* 14.5, 6.0 and 1.8, 5-H), 2.88 (1 H, dd, B-part of AB-system, *J* 14.5, 7.8, 5-H); δ_C(50 MHz, $CDCl_3$, Me_4Si) 170.88, 131.63, 124.37, 56.49, 54.73, 54.16, 53.31, 51.21 and 25.88; ν_{max}(NaCl)/cm^{-1} 3000, 3010, 2990, 2980, 1690 and 1450 (Found: C, 59.15; H, 5.7. $C_9H_{10}O_4$ requires C, 59.3; H, 5.5%).

Methyl (1α,2α,4α,8α)-3,9-dioxatricyclo[6.1.0.0^{2,4}]non-5-ene-5-carboxylate 42. Product (310 mg, 62%) had mp 88–90 °C from diethyl ether–hexane (1:1); δ_H(200 MHz, $CDCl_3$, Me_4Si) 6.95 (1 H, t, *J* 6.8, 6-H), 4.0 (1 H, d, *J* 2.4, 4-H), 3.77 (3 H, s, CO_2Me), 3.6 (dd, *J* 4.0 and 2.4, 2-H), 3.27 (1 H, dd, *J* 4.1 and 2.4, 1-H), 3.08 (1 H, m, 8-H), 2.92 (1 H, dt, A-part of AB-system, *J* 15.5 and 6.8, 7-H) and 2.70 (1 H, ddd, B-part of AB-system, *J* 15.5, 7.1 and 4.5, 7-H); δ_C(50 MHz, $CDCl_3$, Me_4Si) 166.24, 140.76, 129.80, 53.55, 52.63, 52.17, 50.76, 49.73 and 25.87; ν_{max}(NaCl)/cm^{-1} 3000, 2990, 2980, 1695, 1405 and 1230 (Found: C, 59.0; H, 5.7. $C_9H_{10}O_4$ requires C, 59.3; H, 5.5%).

Methyl (1α,2α,4α,8α)-3,9-dioxatricyclo[6.1.0.0^{2,4}]non-5-ene-1-carboxylate 43. Product (285 mg, 57%) had mp 79–81 °C from diethyl ether–hexane (1:1); δ_H(200 MHz, $CDCl_3$, Me_4Si) 5.85 (2 H, m, 5-H and 6-H), 3.98 (1 H, d, *J* 2.4, 2-H), 3.81 (3 H, s, CO_2Me), 3.58 (m, 4-H), 3.35 (t, *J* 6.0, 8-H), 2.92 (1 H, m, A-part of AB-system, H-7) and 2.60 (1 H, m, B-part of AB-system, H-7); δ_C(50 MHz, $CDCl_3$, Me_4Si) 170.14, 129.23, 125.52, 56.15, 55.20, 54.18, 53.00, 52.12 and 25.95; ν_{max}(NaCl)/cm^{-1} 3040, 2990, 2980, 1720, 1440 and 1230 (Found: C, 59.2; H, 5.35. $C_9H_{10}O_4$ requires C, 59.3; H, 5.5%).

Methyl (1α,2α,4α,8α)-3,9-dioxatricyclo[6.1.0.0^{2,4}]non-6-ene-1-carboxylate 44. Product (375 mg, 74%) had δ_H(200 MHz, $CDCl_3$, Me_4Si) 5.86 (1 H, dt, A-part of AB-system, *J* 10.2 and 6.4, 6-H), 5.70 (1 H, ddd, B-part of AB-system, *J* 10.2, 3.6 and 1.6, 7-H), 3.7–3.9 (2 H, m, 2-H and 8-H), 3.8 (3 H, s, CO_2Me), 3.2 (1 H, m, 4-H), 2.85 (1 H, ddt, *J* 14.8, 6.4 and 1.6, 5-H) and 2.55 (1 H, ddd, *J* 14.8, 7.3 and 5.6, 5-H); δ_C(50 MHz, $CDCl_3$, Me_4Si) 170.11, 129.88, 124.76, 56.18, 56.05, 55.82, 54.42, 52.56 and 25.12; ν_{max}(NaCl)/cm^{-1} 3040, 2990, 2980, 1715, 1440 and 1240 (Found: C, 59.45; H, 5.3. $C_9H_{10}O_4$ requires C, 59.3; H, 5.5%).

General procedure for CoTPP-catalysed reaction of the endoperoxides 18, 19, 22, 23, 26, 27 and 31

To a magnetically stirred solution of the endoperoxide (5.5 mmol) in CH_2Cl_2 (50 ml) was added a solution of cobalt *meso*-tetraphenylporpyrin[18] (50 mg, 0.1 mmol) in CH_2Cl_2 (20 ml) at 0 °C. After complete addition (15 min), the mixture was stirred for 30 min at room temperature and then roto-evaporated. Low-temperature chromatography of the residue on silica gel (50–75 g) with ethyl acetate–hexane (1:9) as eluent at 0 °C yielded the corresponding bis-epoxides or a mixture of epoxides and aldehydes.

General procedure for thermolysis of compounds 47, 49 and 51

A solution of each of the divinyl epoxides in CCl_4 (5 ml) was heated at 45 °C. The reaction, monitored by ^{1}H NMR spectroscopy, was complete after 1 h. The conversion of the *cis*-aldehydes **47**, **49** and **51** into the corresponding 4,5-dihydrooxepines **48**, **50** and **52** was in quantitative yield.

CoTPP-catalysed reaction of 19

The products were (1) compound **39** (710 mg, 71%), (2) compound **47** colourless liquid (110 mg, 11%) and (3) compound **48** colourless liquid (35 mg, 3.5%).

4,5-*cis*-Epoxy-6-acetylocta-2(*Z*),6-dienal 47. δ_H(200 MHz, $CDCl_3$, Me_4Si) 10.16 (1 H, dd, *J* 5.0 and 2.7, CHO), 6.26 (1 H, br s, 7-H), 6.12 (2 H, m, 2-H and 3-H), 6.06 (1 H, br s, 7-H), 4.36 (1 H, dt, *J* 4.5 and 1.9, 4-H), 4.14 (1 H, br d, *J* 1.9, 5-H), 2.39 (3 H, s, COMe); δ_C(50 MHz, $CDCl_3$, Me_4Si) 198.16, 192.66, 142.31, 141.43, 135.67, 123.82, 58.24, 54.35 and 24.42.

3-Acetyl-5-formyl-4,5-dihydrooxepine 48. A colourless liquid, δ_H(200 MHz, $CDCl_3$, Me_4Si) 9.53 (1 H, s, CHO), 7.55 (1 H, s, 2-H), 6.43 (1 H, dd, *J* 7.5 and 1.7, 7-H), 5.32 (1 H, dd, *J* 7.5 and 5.1, 6-H), 3.30 (1 H, m, 5-H), 3.15 (1 H, dd, *J* 15.3 and 2.9, 4-H), 2.72 (1 H, dd, *J* 15.3 and 7.7, 4-H) and 2.32 (3 H, s, COMe); δ_C(50 MHz, $CDCl_3$, Me_4Si) 200.12, 198.31, 158.53, 142.29, 121.34, 107.28, 49.81, 26.28 and 26.12 (Found: C, 58.95; H, 5.40. $C_9H_{10}O_4$ requires C, 59.3; H, 5.5%).

CoTPP-catalysed reaction of 26

The products were (1) compound **42** (325 mg, 65%) and (2) compound **49** colourless liquid (125 mg, 25%).

4,5-*cis*-Epoxy-5-methoxycarbonylocta-2(*Z*),6-dienal 49. δ_H(200 MHz, $CDCl_3$, Me_4Si) 10.15 (1 H, br d, CHO), 6.25 (3 H, m, 2-H, 3-H and 6-H), 5.51 (2 H, m, 7-H), 4.55 (1 H, d, 4-H) and 3.85 (3 H, s, CO_2Me); δ_C(50 MHz, $CDCl_3$, Me_4Si) 192.18, 166.32, 141.33, 138.16, 136.41, 121.18, 61.72, 58.63 and 52.24.

Methyl 5-formyl-4,5-dihydrooxepine-2-carboxylate 50. Colourless liquid δ_H(200 MHz, $CDCl_3$, Me_4Si) 9.81 (1 H, d, CHO), 6.48 (1 H, t, *J* 6.6, 3-H), 6.45 (1 H, dd, *J* 7.7 and 1.6, 7-H), 5.18 (1 H, dd, *J* 7.6 and 5.6, 6-H), 3.91 (3 H, s, CO_2Me), 3.37 (1 H, m, 5-H), 2.72 (1 H, ddd, A-part of AB-system, *J* 17.5, 7.5 and 3.5, 4-H) and 2.65 (1 H, dt, *J* 17.5, 6.8, 4-H); δ_C(50 MHz, $CDCl_3$, Me_4Si) 199.75, 163.85, 145.17, 144.52, 119.46, 115.60, 53.80, 50.85 and 26.32 (Found: C, 59.7; H, 5.35. $C_9H_{10}O_4$ requires C, 59.3; H, 5.5%).

CoTPP-catalysed reaction of 31

The products were (1) compound **44** colourless liquid (310 mg, 62%) and (2) compound **51** colourless liquid (151 mg, 30%).

4,5-*cis*-Epoxy-3-methoxycarbonylocta-2(*Z*),6-dienal 51. δ_H(200 MHz, $CDCl_3$, Me_4Si) 10.45 (1 H, d, *J* 7.4, CHO), 6.74 (1H, d, *J* 7.4, 2-H), 5.62 (2 H, m), 5.40 (1 H, m), 3.89 (1 H, d, *J* 1.9, 4-H), 3.85 (3 H, s, CO_2Me) and 3.35 (1 H, dd, *J* 7.4, 1.9, 5-H); δ_C(50 MHz, $CDCl_3$, Me_4Si) 192.35, 165.88, 142.18, 136.42, 134.08, 120.12, 60.87, 58.90 and 52.57.

Methyl 4-formyl-4,5-dihydrooxepine-3-carboxylate 52. δ_H(200 MHz, $CDCl_3$, Me_4Si) 9.51 (1 H, br s, CHO), 7.76 (1 H, s, 2-H), 6.20 (1 H, dd, *J* 7.4 and 2.4, 7-H), 5.09 (1 H, dt, *J* 7.4 and 3.7, 6-H), 4.12 (1 H, t, *J* 3.7, 4-H), 3.76 (3 H, s, CO_2Me), 2.65 (1 H, ddd, A-part of AB-system, *J* 14.8, 7.4 and 3.7, 5-H) and 2.54 (1 H, ddt, *J* 14.8, 7.4, 3.3, 5-H); δ_C(50 MHz, $CDCl_3$, Me_4Si) 199.55, 168.37, 156.15, 142.44, 109.32, 108.56, 68.17, 52.15 and 25.83 (Found: C, 59.9; H, 5.35. $C_9H_{10}O_4$ requires C, 59.3; H, 5.5%).

Acknowledgements

The authors are indebted to the Department of Chemistry (Atatürk University) for financial support of this work and the State Planning Organization of Turkey (DPT) for purchasing a 200 MHz spectrometer. Also, appreciation must be expressed to Professor P. Shevlin for his hospitality at Auburn University where this manuscript was prepared. Furthermore, we thank Dr Katherine Seley for critical reading of this manuscript.

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Paper 7/01105I
Received 17*th February* 1997
Accepted 10*th April* 1997