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Use of a highly effective intramolecular Pauson–Khand cyclisation for the formal total synthesis of (±)-α- and β-cedrene by preparation of cedrone

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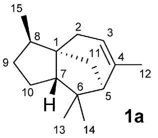
Dedicated with warmth and the utmost respect to our fellow countryman, Professor David W. MacMillan, in recognition of his broad and outstanding contributions to organic synthesis and on the occasion of being honoured with the first Tetrahedron Young Investigator Award

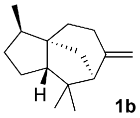
Abstract—The cedrene carbon skeleton was directly and efficiently assembled from a simple monocyclic precursor by the strategic use of a high yielding intramolecular Pauson–Khand cyclisation reaction. A small number of further synthetic manipulations provided a concise formal total synthesis of α- and β-cedrene. The cyclisation precursor was readily prepared, with a stereoselective ketone alkenylation selectively providing the olefin required for efficient access to the natural target.

1. Introduction

The tricyclic sesquiterpenes α-cedrene **1a** and β-cedrene **1b** can be isolated from *Juniperus cedrus* and *Juniperus thurifera*, alongside a variety of closely related oxygenated terpenoid analogues.[1] Driven by the intriguing and preparatively challenging [5.3.1.0^{1,5}] tricyclic structure, the cedrene family of natural products has been the focus of considerable synthetic endeavours[2] over the years since initial characterisation in 1953. As part of our continuing series of studies to further develop the overall effectiveness and applicability of the Pauson–Khand[†] annulation reaction,[3] we sought to utilise this cyclisation process as the central synthetic transformation within routes towards α-cedrene **1a** and, in so doing, establish a direct and efficient pathway for the synthesis of this structurally demanding tricyclic skeleton. Following the preliminary communication of our initial endeavours towards these goals,[4] we have subsequently made key improvements to the overall selectivity and effectiveness of our preparative pathway. Full details of our revised synthetic approaches to this class of tricyclic sesquiterpene natural product are now presented.



1a



1b

2. Results and discussion

2.1. Initial synthetic approaches to the Pauson–Khand cyclisation precursor

Our synthetic approach is initiated with the introduction of α,β-unsaturation into the commercially available cyclohexanedione monoethylene acetal **2** (Scheme 1). Following straightforward preparation of the enol ether **3**, Saegusa oxidation[5] afforded the enone **4**. More specifically, use of stoichiometric quantities of palladium(II) acetate, provided the enone **4** in 92% yield. On the other hand, the considerably more economical catalytic modification[6] of this useful transformation was investigated and delivered **4** in a respectable 82% yield, whilst requiring the use of only 5 mol % of palladium(II) acetate. With the desired enone in hand, ytterbium(III) triflate trihydrate-catalysed[7] 1,4-addition of the trimethylsilyl enol ether of ethyl isobutyrate directly

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Keywords: Pauson–Khand reaction; Cedrene; Tricyclic sesquiterpene; Stereoselective Wittig reaction; Cobalt.

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[†] Hitherto one of us has preferred to use the initially designated name of 'Khand' reaction for this synthetic process; in light of what has now become common usage and following comments from the referees, we have subsequently employed the more widely accepted term 'Pauson–Khand' throughout this paper.

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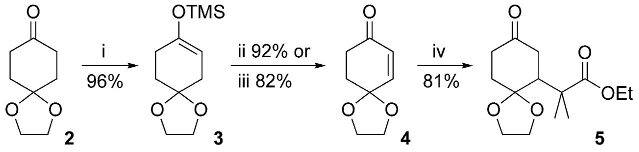
afforded the ester **5** in a yield of 81%. Use of the anhydrous form of ytterbium(III) triflate led to the isolation of the trimethylsilyl enol ether of ketone **5**, from the direct silylation of the enolate resulting from conjugate addition, as a by-product (cf. compound **13** vide infra). It should also be noted that employment of the more commonly used titanium tetrachloride as a stoichiometric mediator of this type of Michael addition resulted in unwanted removal of the ketone protection, even at −78 °C.

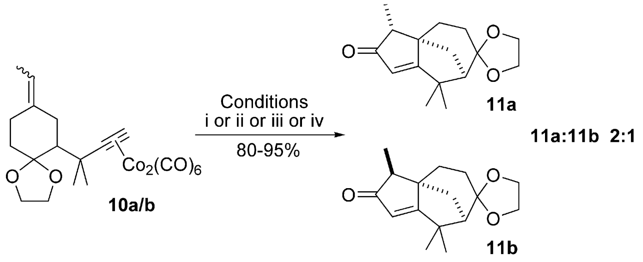


Scheme 1. Reagents and conditions: (i) TMSOTf, Et_3N, DCM, −5 °C, 15 min; (ii) 1.05 equiv $Pd(OAc)_2$, CH_3CN, rt, 24 h; (iii) 5 mol % $Pd(OAc)_2$, DPPE, 1.4 equiv diallyl carbonate, CH_3CN, 81 °C, 40 h; (iv) 10 mol % $Yb(OTf)_3\cdot 3H_2O$, $Me_2CC(OEt)OTMS$, DCM, rt, 24 h.

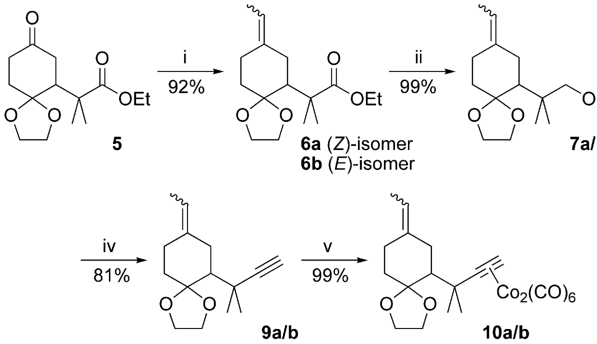
Ethylidenation of the ketone carbonyl of **5** was now considered as the next step in our synthetic sequence. Indeed, this was viewed as a key transformation in a stereochemical sense, with the (*E*)-isomer **6b** being required to provide the requisite orientation of the C-15 methyl group of α-cedrene **1a**. Using the ethyltriphenylphosphonium bromide salt and *n*-butyllithium with ketone **5** in a standard Wittig process at 0 °C, a 92% yield of olefins **6a/6b** was obtained, as a 2:1 mixture of geometric isomers (Scheme 2). Since the products **6a** and **6b** were inseparable, they were employed in combination to allow the planned synthetic route to be established and with a view to identification of individual isomers at a later stage. In this respect and as shown in Scheme 2, total reduction of the ester functionality of **6a/6b** with lithium aluminium hydride delivered alcohols **7a/7b** in 99% yield. This was followed by oxidation to aldehydes **8a/8b** in a yield of 97% using the Dess–Martin periodinane.[8] For the conversion of aldehydes into alkynes, previous studies in our laboratory had shown the Ohira–Bestmann technique (with the reagent dimethyl acetyldiazomethylphosphonate)[9] to be practically accessible and effective. In this instance, this mild protocol delivered alkynes **9a/9b** in 81% yield. In turn, these were routinely complexed with octacarbonyldicobalt to furnish the stable cyclisation precursors **10a/10b** in almost quantitative yield. At this stage and with the requisite complexes in hand, the proposed Pauson–Khand annulation for the assembly of the desired tricyclic carbon α-cedrene skeleton could now be investigated.

2.2. Pauson–Khand cyclisations to the tricyclic cedrene skeleton

A series of techniques for promoting the key intramolecular Pauson–Khand cyclisation of **10a/10b** were probed. As shown in Scheme 3, two different amine *N*-oxides were employed at room temperature,[10] a soluble alkyl methyl sulfide was used under more forcing conditions,[11] and our more recently developed solid-supported alkyl methyl sulfide was also applied.[3i] To our delight, in every instance, the Pauson–Khand cyclisation took place smoothly to provide the enones **11a/11b** in high yield. This clearly demonstrates the novel applicability of this annulation process to the direct construction of such complex tricyclic systems from simple monocyclic substrates. The optimum Pauson–Khand annulation yield of 95% was achieved using Sugihara's technique with the soluble *n*-butyl methyl sulfide in 1,2-DCE at reflux.[11] The alternative polymer-supported sulfide provided a somewhat reduced yield of 80% for the same cyclisation. Having stated this, it is worth noting that the work-up procedure with this solid-phase reagent was greatly facilitated by the ability of the resin-based species to sequester the unwanted cobalt residues, enabling removal of these by-products by simple filtration. It is important to point out that our key Pauson–Khand cyclisation could also be achieved very effectively at room temperature. In this respect, the commercially available dihydrate of trimethylamine *N*-oxide (TMANO·2H_2O) and the monohydrate of *N*-methylmorpholine *N*-oxide (NMO·H_2O) afforded cyclopentenones **11a/11b** in high yields of 91% and 84%, respectively.



Scheme 3. Reagents and conditions: (i) 9 equiv TMANO·2H_2O, acetone, rt, 16 h, 91%; (ii) 8 equiv NMO·H_2O, DCM, rt, 16 h, 84%; (iii) 4.3 equiv *n*-BuSMe, 1,2-DCE, 83 °C, 30 min, 95%; (iv) 3.6 equiv polymer-supported sulfide, 1,2-DCE, 83 °C, 30 min, 80%.



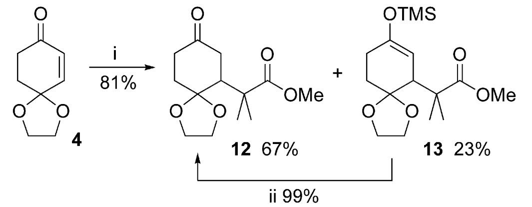
Scheme 2. Reagents and conditions: (i) $Ph_3P^+CH_2CH_3\ Br^-$, *n*-BuLi, THF, 0 °C, 2 h; (ii) $LiAlH_4$, Et_2O, 0 °C, 1 h; (iii) Dess–Martin periodinane, 10% CH_3CN in DCM, rt, 1 h; (iv) $AcC(N_2)P(O)(OMe)_2$, K_2CO_3, MeOH, rt, 5 d; (v) $Co_2(CO)_8$, petrol, rt, 2 h.

As shown in Scheme 3, the product cyclopentenones **11a/11b** were obtained as a mixture of stereoisomers in a ratio of 2:1. This indicated that the relative stereochemistry present in the initial olefins **6a/6b** had been carried through to cyclisation precursors **10a/10b** and onto the Pauson–Khand products without change. At this stage, the diastereomers **11a/11b** were now separable by silica column chromatography and the individual cyclopentenones were independently characterised by X-ray crystallographic analyses.[12] Disappointingly, the major isomer **11a** featured the (C-15) methyl group, adjacent to the carbonyl, with the undesired (α) stereochemistry, whilst the minor isomer **11b** possessed the required methyl group (β) orientation. Therefore, despite the excellent levels of efficiency realised for the Pauson–Khand cyclisation process, this stereochemical elucidation and outcome identified a clearly limiting feature of our synthetic route to this stage.

2.3. Probing the stereoselectivity of the key Wittig olefination process

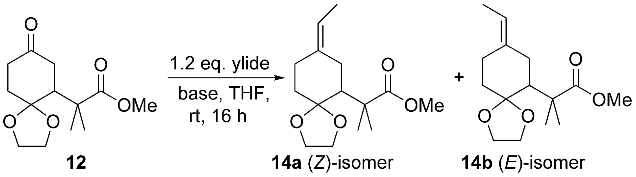
Having made the assignments of relative stereochemistry within **11a** and **11b**, it was now apparent that the specific ratio of olefin geometric isomers achieved through ethylidenation of **5** (as shown in Scheme 2) was 2:1 (*Z*)-**6a**:(*E*)-**6b**. Accordingly, endeavours to access enhanced proportions of the requisite *E*-isomer (**6b**) and a generally more useful isomer ratio, in relation to the synthesis of α-cedrene, were required. In this regard and as part of preliminary investigations, simply utilising a lower olefination reaction temperature of −78 °C, with *n*-butyllithium again being used as base, did not affect the alkene stereoisomeric ratio obtained. Furthermore, use of weaker bases (e.g., K_2CO_3, KOH, NaOEt) in protic solvents (e.g., EtOH) at higher temperatures proved ineffective.

At this stage it was clear that a more detailed exploration of the Wittig olefination process was required. Having stated this and prior to any investigation into the stereoselectivity of olefin formation, it was recognised that use of the ethyl ester **5** did not readily allow use of ^{1}H NMR techniques for the determination of the product alkene ratios. Indeed, to this stage in the programme, analysis of isomeric olefin ratios had been performed by ^{13}C NMR integration. Whilst this had proved reliable, in the sense that the olefin mixtures had been carried through the synthetic scheme and the ratios confirmed as detailed above, a clearly more readily utilisable ^{1}H NMR spectroscopic method for alkene composition determination was desired. To this end, the equivalent methyl ester **12** was routinely prepared as shown in Scheme 4; in this process, once again using hydrated ytterbium(III) triflate as catalyst with enone **4**, the desired keto ester **12** was prepared in 67% yield, along with a 23% yield of the silyl enol ether **13**. This latter species was readily converted to the ester **12** in 99% yield under mild conditions with 2% aqueous oxalic acid, leaving the acetal protecting group intact.



Scheme 4. Reagents and conditions: (i) 10 mol % $Yb(OTf)_3\cdot 3H_2O$, $Me_2CC(OMe)OTMS$, DCM, rt, 24 h; (ii) 2% aq oxalic acid, Et_2O, rt, 12 h.

First of all, in order to obtain a direct comparison with the ethyl ester **5**, the methyl ester **12** was subjected to olefination conditions, which were almost identical to those previously employed as part of the initial synthetic route towards the Pauson–Khand cyclisation precursor. More specifically, use of the ethyltriphenylphosphonium bromide salt and *n*-butyllithium with **12** at room temperature (Scheme 5, Table 1, Entry 1) delivered the alkenes **14a** and **14b** in similar yield and selectivity (89% and 1.6:1; **14a**:**14b**) to that obtained with the equivalent ethyl ester precursor **5** (with olefin ratios being determined by ^{1}H NMR spectroscopy; see Section 4).



Scheme 5. Wittig olefination of keto methyl ester **12**; see Table 1.

Table 1. Wittig olefination of keto methyl ester **12**

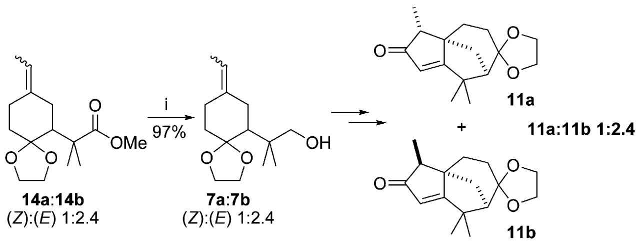
Entry	Ylide	Base	Yield (%)	Ratio **14a**:**14b**
1	$Ph_3P^+Et\ Br^-$	*n*-BuLi	89	1.6:1
2	$Ph_3P^+Et\ Br^-$	NaHMDS	77	1:2.4
3	$Ph_3P^+Et\ Br^-$	KHMDS	85	1:2.3
4	$Ph_3P^+Et\ Cl^-$	KHMDS	79	1:2.3
5	$Ph_3P^+Et\ I^-$	KHMDS	90	1:2.3
6	$Ph_3P^+Et\ Cl^-$	NaHMDS	75	1:2.5
7	$Et_4P^+\ Br^-$	NaHMDS	75	1:1.1
8	$Et_4P^+\ Br^-$	KHMDS	75	1:1.1

In a very general sense, the efficiency and stereoselectivity of Wittig olefination reactions are known to be affected by the type of ylide used, the base employed, the carbonyl compound, the reaction solvent, and the base/ylide metal counter ion.[13] Whilst olefin stereoselectivity studies have focused on the use of aldehyde substrates within the Wittig process, the parameters and reaction components listed were considered for investigation with the requisite starting cyclic ketone as part of this programme. In this respect, with aldehydes, the use of 'salt-free' conditions (traditionally defined as the absence of lithium salts) is known to enhance the *Z*-selectivity of Wittig olefinations.[13,14] In contrast, the presence of lithium salts, as in the Wittig processes described to this stage, is known to deplete this stereoselectivity. Based on this, we moved to simply amend the counter ion associated with the bases used. Remarkably, when NaHMDS and KHMDS were employed with the same Wittig salt and keto ester **12**, the selectivity of our olefination process was completely reversed, with the desired alkene **14b** now being formed predominantly over **14a** (Table 1, Entries 2 and 3) in ratios of 1:2.4 and 1:2.3, respectively. Considering the minimal local differences on either side of the ketonic carbonyl group, these observed selectivities are even more notable. Amendment of the halide counter ion associated with the Wittig salt moderately affected yields (Table 1, Entries 4–6) but did deliver the maximum **14a**:**14b** ratio of 1:2.5 (Entry 6). Overall, these were exceedingly pleasing outcomes from such a simple change in reagents and, more importantly, overturned the only significant inefficiency in the synthetic approach to α-cedrene as previously described.[4]

Finally in this area, Schlosser has shown how the replacement of triarylphosphonium ylides with trialkylphosphonium species can, again, considerably affect the stereoselectivity of such olefination processes.[15] When the tetraethylphosphonium bromide salt was utilised with both NaHMDS and KHMDS, the ratios of alkenes produced (1:1.1; **14a**:**14b**; Table 1, Entries 7 and 8) provided no further preparative advantages in this synthetic programme. Additionally, the application of a number of alternative solvents (e.g., DME, glyme) and additives (e.g., 18-c-6) did nothing to further enhance the proportion of **14b** formed over that described above.

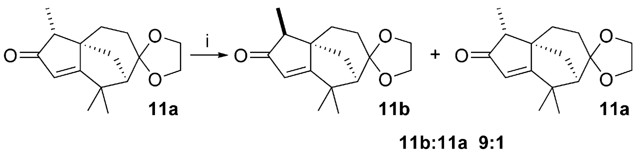
2.4. Selective access to the desired cyclopentenone epimer 11b

From that described above, the desired olefin for use in the α-cedrene synthesis could now be formed predominately and in ratios of up to 1:2.5 (**14a**:**14b**). With this more favourable and selective olefination procedure in place and with a view to complete confirmation of our olefin stereochemical assignments, an isomerically-enriched alkene mixture (1:2.4; **14a**:**14b**) was taken on in the synthetic pathway, as described previously. In this respect, $LiAlH_4$ reduction of **14a/14b** proceeded in excellent yield to deliver **7a/7b**, with the same olefinic ratio of 1:2.4 being observed (Scheme 6). From this point the remainder of the synthetic pathway (as described in Scheme 2) proceeded without complication. Gratifyingly, on Pauson–Khand cyclisation and stereoisomer separation, a 1:2.4 ratio of the undesired cyclopentone **11a** to the required epimer **11b** was obtained.



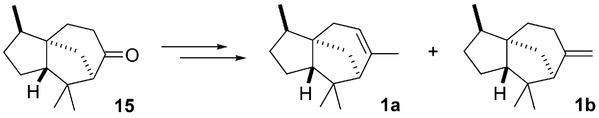
Scheme 6. Reagents and conditions: (i) $LiAlH_4$, Et_2O, rt, 1 h.

As described to this stage, the desired cyclopentenone **11b** could now be accessed in excellent yield and in appreciable excess. Despite this, since isomeric mixtures from olefins **14a/14b** were carried through the synthesis, quantities of the undesired cyclisation product **11a** were also produced. In order to further enhance the overall effectiveness of our route towards the cedrene natural products, a simple α-methyl epimerisation process was attempted. Following a very short exploratory programme, it was found that optimal efficiency was provided by utilising LiOH in a refluxing mixture of THF and H_2O. This almost completely transformed the unwanted stereoisomer **11a** into the desired cyclopentenone **11b** and generated a separable 1:9 mixture of undesired to desired stereoisomers in quantitative yield (Scheme 7). Consequently, this provided further amplification of the efficiency of the overall synthetic pathway described here. Moreover, separation of these isomers and further epimerisation was facilitated allowing, in theory, near complete transformation to the desired isomer over several runs.

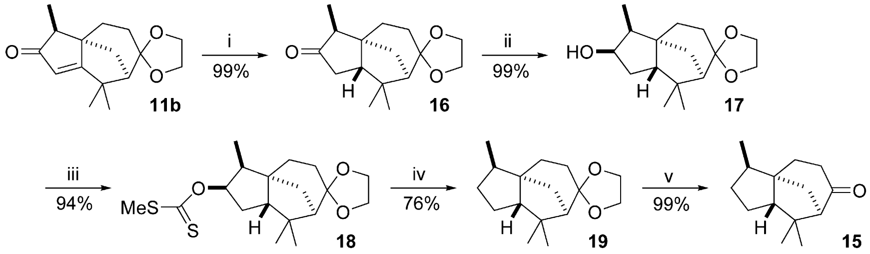


Scheme 7. Reagents and conditions: (i) LiOH, THF/H_2O (5:1), reflux, 3 d.

2.5. Formal total synthesis of α-cedrene 1a and β-cedrene 1b



In a number of instances α-cedrene **1a** (and β-cedrene **1b**) have been readily accessed in two steps from cedrone **15**[2a,e,h] and, consequently, preparation of this latter compound from the key Pauson–Khand cyclisation product would complete our formal total synthesis of the natural sesquiterpenes. With an efficient and selective route to **11b** now having been established, this cyclopentenone was subjected to palladium-catalysed hydrogenation to give **16** in 99% yield (Scheme 8). This reduction process proved to be completely stereoselective, with the relative stereochemistry present in this saturated tricyclic skeleton, again, being confirmed by X-ray analysis.[12] As shown, the newly introduced bridgehead H-atom (at C-7) has the requisite stereochemistry. In due course, lithium aluminium hydride reduction of the carbonyl functionality of **16** was achieved in an excellent 99% yield; at the 0 °C reaction temperature this protocol was totally selective and afforded only one detectable alcohol isomer, tentatively assigned as compound **17**. In turn, the secondary alcohol **17** was reduced following the well-established Barton–McCombie method.[16] In this respect, the xanthate ester intermediate **18** was formed very readily, and the required deoxygenated product **19** was obtained when **18** was treated with tributyltin hydride in the presence of a catalytic amount of AIBN initiator, using degassed benzene as solvent, and in a yield of 71% over the two steps. Finally, the ketone protection was removed using mild conditions, as discovered in our own laboratories, which involved the use of sub-stoichiometric quantities of carbon tetrabromide and triphenylphosphine in acetone.[17] This delivered the desired cedrone target **15** in 99% yield, to complete our concise formal total synthesis of α- and β-cedrene, **1a** and **1b**.



Scheme 8. Reagents and conditions: (i) 10% Pd/C, H_2 (45 psi), toluene, rt, 3 h; (ii) $LiAlH_4$, Et_2O, 0 °C, 2 h; (iii) *n*-BuLi, CS_2, MeI, 0 °C–rt, 110 min; (iv) Bu_3SnH, AIBN, degassed C_6H_6, 80 °C, 48 h; (v) 8 mol % Ph_3P/CBr_4, acetone, rt, 1 h.

3. Conclusions

We have now shown that strategic use of an intramolecular Pauson–Khand reaction, with a simple monocyclic precursor, can allow the direct and highly efficient construction of the challenging tricyclic $[5.3.1.0^{1,5}]$ carbon skeleton of α-cedrene **1a** (and β-cedrene **1b**). Furthermore, the overall efficiency of this approach has been considerably enhanced by the ability to reverse the originally observed selectivity of the central Wittig olefination procedure on the requisite cyclic ketone intermediate. In the key Pauson–Khand annulation process, the olefinic precursors react with retention of stereochemistry to deliver the desired cyclopentenone epimer, for synthesis of the targeted natural products, in excess. To further amplify the efficiency of this overall synthetic programme, the residual and undesired cyclopentenone product was also shuttled through to the required isomer by a simple base-mediated epimerisation process. In turn, the desired cyclopentenone intermediate so obtained was further elaborated to cedrone **15**, thus constituting a formal total synthesis of α- and β-cedrene. Finally, it is also worth noting that compound **11a** was subjected to a sequence of reactions similar to those performed on **11b** to deliver a synthesis of *epi*-cedrone.

4. Experimental

4.1. General

Dry tetrahydrofuran (THF) and diethyl ether (Et_2O) were obtained by distilling commercial solvents from sodium benzophenone ketyl and dichloromethane (CH_2Cl_2) was distilled from calcium hydride. Light petroleum refers to the fraction of bp 30–40 °C and was distilled prior to use. All organometallic complexes were stored under nitrogen at, or below, −20 °C and all reactions were performed under a nitrogen atmosphere unless otherwise stated. ^1H and ^{13}C NMR were run on a Bruker WM 250 and a Bruker WM 400 in $CDCl_3$ solutions. Chemical shifts are reported in parts per million downfield relative to tetramethylsilane (δ 0.00); coupling constants are reported in hertz. Infrared spectra were obtained on a Mattson 1000 or Nicolet Impact 400D FTIR spectrometer in CH_2Cl_2 solutions or as films. High resolution mass spectrometry was performed on a JEOL Instruments JMS-AX505HA mass spectrometer system or a Finnigan MAT 900XLT high resolution double focussing mass spectrometer. Mass spectral data are reported as *m*/*z*.

4.1.1. 8-((Trimethylsilyl)oxy)-1,4-dioxaspiro[4.5]dec-7-ene 3. A solution of trimethylsilyl trifluoromethanesulfonate (1.86 g, 1.52 ml, 8.39 mmol) in dichloromethane (20 ml) was added over a 10 min period to a stirred solution of 1,4-dioxaspiro[4.5]decan-8-one **2** (1.19 g, 7.63 mmol) and triethylamine (2.30 g, 3.30 ml, 22.9 mmol) in dichloromethane (70 ml) at −5 °C. The mixture was stirred for 15 min before the reaction was quenched by the addition of saturated aqueous sodium hydrogen carbonate solution (5 ml) and then water (35 ml). The organic phase was separated, dried, and evaporated under reduced pressure to leave a crude residue, which was extracted with light petroleum (3×20 ml). The light petroleum extracts were combined and filtered through a pad of silica using light petroleum as the eluent. The filtrate was evaporated under reduced pressure to give *8-((trimethylsilyl)oxy)-1,4-dioxaspiro[4.5]dec-7-ene* **3** (1.67 g, 96%) as a colourless oil. IR ν_{max} (film)/cm^{-1} 1664 (C=C); ^1H NMR (400 MHz, $CDCl_3$): δ 0.19 (9H, s, $(CH_3)_3Si$), 1.81 (2H, t, *J* 6.6, C^{10}-H), 2.20 (2H, m, C^9-H), 2.26 (2H, m, C^6-H), 3.97 (4H, m, $C^{2,3}$-H) and 4.73 (1H, m, C^7-H); ^{13}C NMR (100 MHz, $CDCl_3$): δ 0.5 ($(CH_3)_3Si$), 28.7, 31.3, 34.1, 64.6 ($C^{2,3}$), 100.8 (C^7), 107.9 (C^5) and 150.0 (C^8); HRMS (EI) *m*/*z* Calcd for $C_{11}H_{20}O_3Si$ (M^+): 228.1182. Found: 228.1181.

4.1.2. 1,4-Dioxaspiro[4.5]dec-6-en-8-one 4. Palladium(II) acetate (1.03 g, 4.60 mmol) was added to a solution of 8-((trimethylsilyl)oxy)-1,4-dioxaspiro[4.5]dec-7-ene **3** (1.00 g, 4.39 mmol) in acetonitrile (70 ml) and the mixture was stirred for 24 h at 25 °C. The solvent was then evaporated under reduced pressure and the black residue was filtered through a pad of silica using dichloromethane as the eluent. The filtrate was washed with saturated aqueous sodium hydrogen carbonate solution (50 ml) to remove traces of acetic acid. The organic phase was dried and evaporated under reduced pressure to give *1,4-dioxaspiro[4.5]dec-6-en-8-one* **4** (0.62 g, 92%) as a pale yellow oil. Found: C, 62.31; H, 6.35. $C_8H_{10}O_3$ requires C, 62.30; H, 6.50%; IR ν_{max} (film)/cm^{-1} 1683 (C=O); ^1H NMR (400 MHz, $CDCl_3$): δ 2.20 (2H, t, *J* 6.5, C^{10}-H), 2.63 (2H, t, *J* 6.5, C^9-H), 4.05 (4H, m, $C^{2,3}$-H), 6.00 (1H, d, *J* 10.2, C^7-H) and 6.61 (1H, d, *J* 10.2, C^6-H); ^{13}C NMR (100 MHz, $CDCl_3$): δ 33.0, 35.4, 65.2 ($C^{2,3}$), 104.1 (C^5), 130.6 (C^7), 146.6 (C^6) and 198.8 (C^8); HRMS (EI) *m*/*z* Calcd for $C_8H_{11}O_3$ (M^++1): 155.0708. Found: 155.0710.

Compound **4** was also prepared by the following method: a solution of palladium(II) acetate (36.0 mg, 0.16 mmol) and 1,2-bis-(diphenylphosphino)ethane (58.0 mg, 0.14 mmol) in acetonitrile (50 ml) was heated to reflux before diallyl carbonate (0.64 g, 4.51 mmol) and 8-((trimethylsilyl)oxy)-1,4-dioxaspiro[4.5]dec-7-ene **3** (0.74 g, 3.24 mmol) were added. The mixture was heated under reflux for a further 40 h.

The solvent was then evaporated under reduced pressure to leave a crude residue, which was purified by filtration through a pad of silica using 50% diethyl ether in light petroleum as the eluent. The filtrate was then evaporated under reduced pressure to give *1,4-dioxaspiro[4.5]dec-6-en-8-one* **4** (0.41 g, 82%) as a pale yellow oil. Analytical data were as given above.

4.1.3. Ethyl 2-(1,4-dioxaspiro[4.5]decan-8-on-6-yl)-2-methylpropanoate 5. Ytterbium(III) trifluoromethanesulfonate trihydrate (0.06 g, 0.09 mmol) was added to a stirred solution of 1,4-dioxaspiro[4.5]dec-6-en-8-one **4** (0.14 g, 0.91 mmol) and 1-ethoxy-1-((trimethylsilyl)oxy)-2-methylpropene (0.23 g, 1.43 mmol) in dichloromethane (20 ml) at 25 °C. The mixture was stirred for 24 h before it was filtered through a pad of silica using diethyl ether as the eluent. The filtrate was evaporated under reduced pressure to leave a crude residue, which was purified by column chromatography on silica using a 10–50% diethyl ether in light petroleum gradient as the eluent to give *ethyl 2-(1,4-dioxaspiro[4.5]decan-8-on-6-yl)-2-methylpropanoate* **5** (0.20 g, 81%) as a pale yellow oil. IR ν_{max} (film)/cm^{-1} 1721 (C=O) and 1689 (C=O); ^{1}H NMR (400 MHz, $CDCl_3$): δ 1.10 (3H, s, CH_3C), 1.13 (3H, s, CH_3C), 1.24 (3H, t, *J* 7.1, $C\mathit{H}_3CH_2$), 1.74 (1H, app dt, *J* 13.5 and 5.5), 1.99 (1H, m), 2.36 (1H, m), 2.48 (1H, m), 2.58 (2H, t, *J* 13.5), 2.71 (1H, dd, *J* 13.5 and 3.9) and 3.91–4.14 (6H, overlapping m, $CH_3C\mathit{H}_2$, OCH_2CH_2O); ^{13}C NMR (100 MHz, $CDCl_3$): δ 14.3, 19.5, 27.1, 33.5, 38.3, 39.9, 42.6, 48.8, 60.4 ($CH_3\mathit{C}H_2$), 63.6 (OCH_2), 64.8 (OCH_2), 109.6 (OCO), 177.6 (OC=O) and 210.2 (C=O); HRMS (EI) *m/z* Calcd for $C_{14}H_{22}O_5$ (M^+): 270.14672. Found: 270.14603.

4.1.4. Ethyl 2-((*Z*)/(*E*)-8-ethylidene-1,4-dioxaspiro[4.5]-decan-6-yl)-2-methylpropanoate 6a/6b. A solution of *n*-butyllithium in hexanes (2.5 M, 4.90 ml, 12.2 mmol) was added over a 5 min period to a stirred solution of ethyltriphenylphosphonium bromide (4.40 g, 11.8 mmol) in tetrahydrofuran (170 ml) at 0 °C. The resultant orange solution was stirred for 5 min then a solution of ethyl 2-(1,4-dioxaspiro[4.5]decan-8-on-6-yl)-2-methylpropanoate **5** (2.60 g, 9.63 mmol) in tetrahydrofuran (30 ml) was added. The mixture was stirred for a further 2 h before the solvent was evaporated under reduced pressure and replaced by hexanes, causing precipitation of triphenylphosphine oxide. This precipitate was removed by filtration through a pad of silica using 10% diethyl ether in light petroleum as the eluent. The filtrate was evaporated under reduced pressure to leave a residue, which was purified by filtration through a second pad of silica using 10% diethyl ether in light petroleum as the eluent to give *ethyl 2-(8-ethylidene-1,4-dioxaspiro[4.5]-decan-6-yl)-2-methylpropanoate* **6** (2.50 g, 92%) as a pale yellow oil containing both (*Z*)- and (*E*)-isomers in a ratio of 2:1. IR ν_{max} (film)/cm^{-1} 1736 (C=O) and 1450 (C=C); ^{1}H NMR (400 MHz, $CDCl_3$): δ 1.16–1.36 (12H, overlapping m), 1.60 (2H, m), 1.79 (1H, m), 1.96 (1H, m), 2.08–2.28 (2H, overlapping m), 2.51+2.65 (total of 1H, both m), 3.79–4.14 (6H, overlapping m, $CH_3C\mathit{H}_2$, OCH_2CH_2O) and 5.21 (1H, m, $=C\mathit{H}CH_3$); ^{13}C NMR (100 MHz, $CDCl_3$): δ 13.3, 13.5, 14.6, 20.3, 25.1, 25.8, 27.8, 27.9, 33.9, 34.8, 35.8, 36.9, 42.9, 43.1, 51.2, 51.8, 60.4 ($CH_3\mathit{C}H_2$), 60.5 ($CH_3\mathit{C}H_2$), 63.6 ($O\mathit{C}H_2CH_2O$), 64.6 ($OCH_2\mathit{C}H_2O$), 111.6 (OCO), 111.7 (OCO), 117.2 ($=\mathit{C}HCH_3$), 117.6 ($=\mathit{C}HCH_3$), 137.8 ($\mathit{C}=CH$), 137.9 ($\mathit{C}=CH$), 178.8 (OC=O) and 178.9 (OC=O); HRMS (EI) *m/z* Calcd for $C_{16}H_{26}O_4$ (M^+): 282.18311. Found: 282.18408.

4.1.5. (*Z*)/(*E*)-8-Ethylidene-6-(2-methylpropan-1-ol-2-yl)-1,4-dioxaspiro[4.5]decane 7a/7b. Lithium aluminium hydride (0.30 g, 7.81 mmol) was added to a stirred solution of ethyl 2-((*Z*)/(*E*)-8-ethylidene-1,4-dioxaspiro[4.5]decan-6-yl)-2-methylpropanoate **6a/6b** (2.20 g, 7.80 mmol) in diethyl ether (100 ml) at 0 °C and the mixture was stirred for a further 1 h. The reaction was quenched by the addition of water (0.3 ml) then 10% aqueous sodium hydroxide solution (0.3 ml) and lastly another portion of water (0.9 ml). This resulted in a white granular precipitate, which was removed by filtration through a pad of kieselguhr that was washed thoroughly with diethyl ether. The filtrate was evaporated under reduced pressure to give *8-ethylidene-6-(2-methylpropan-1-ol-2-yl)-1,4-dioxaspiro[4.5]decane* **7** (1.86 g, 99%) as a colourless oil containing both (*Z*)- and (*E*)-isomers in a ratio of 2:1. IR ν_{max} (film)/cm^{-1} 3489 (O–H) and 1440 (C=C); ^{1}H NMR (400 MHz, $CDCl_3$): δ 0.83+0.87 (3H, 2×s, 2×CH_3C), 1.01+1.05 (3H, 2×s, 2×CH_3C), 1.31 (1H, dt, *J* 13.4 and 4.8), 1.57 (3H, m), 1.69 (1H, dd, *J* 13.4 and 4.8), 1.83–2.24 (4H, overlapping m), 2.44+2.66 (1H, both m), 3.08 (1H, m), 3.38 (1H, m), 3.55 (1H, m), 3.88–4.22 (4H, overlapping m, OCH_2CH_2O) and 5.16 (1H, m, $=C\mathit{H}CH_3$); ^{13}C NMR (100 MHz, $CDCl_3$): δ 12.8, 13.1, 22.0, 22.1, 24.6, 27.3, 27.5, 33.3, 35.3, 36.1, 36.4, 38.4, 38.6, 47.8, 48.4, 63.0 ($O\mathit{C}H_2CH_2O$), 63.4 ($OCH_2\mathit{C}H_2O$), 71.8 (CH_2OH), 112.9 (OCO), 116.2 ($=\mathit{C}HCH_3$), 116.5 ($=\mathit{C}HCH_3$), 137.8 ($\mathit{C}=CH$) and 138.0 ($\mathit{C}=CH$); HRMS (EI) *m/z* Calcd for $C_{14}H_{24}O_3$ (M^+): 240.17254. Found: 240.17255.

4.1.6. (*Z*)/(*E*)-8-Ethylidene-6-(2-methylpropanal-2-yl)-1,4-dioxaspiro[4.5]decane 8a/8b. The Dess–Martin periodinane (3.26 g, 7.69 mmol) was added to a stirred solution of (*Z*)/(*E*)-8-ethylidene-6-(2-methylpropan-1-ol-2-yl)-1,4-dioxaspiro[4.5]decane (1.50 g, 6.25 mmol) in 10% acetonitrile in dichloromethane (70 ml) at 25 °C. The mixture was stirred for 1 h before the reaction was quenched by the addition of aqueous sodium thiosulfate solution (8.5 g in 20 ml) and saturated aqueous sodium hydrogen carbonate solution (50 ml). This two phase mixture was stirred vigorously for 30 min before the organic phase was separated, dried, and evaporated under reduced pressure to leave a crude residue, which was purified by filtration through a pad of silica using 20% diethyl ether in light petroleum as the eluent. Evaporation of the solvent under reduced pressure gave *8-ethylidene-6-(2-methylpropanal-2-yl)-1,4-dioxaspiro[4.5]decane* **8** (1.44 g, 97%) as a pale yellow oil containing both (*Z*)- and (*E*)-isomers in a ratio of 2:1. IR ν_{max} (film)/cm^{-1} 2819 (aldehyde C–H), 2710 (aldehyde C–H) and 1727 (C=O); ^{1}H NMR (400 MHz, $CDCl_3$): δ 0.99+1.03 (6H, 2×(2×s), 2×(2×CH_3C)), 1.31 (1H, m, $(CH_3)_2CC\mathit{H}$), 1.59 (3H, m, ($=CHC\mathit{H}_3$)), 1.81 (1H, m), 1.91 (1H, m), 2.08 (1H, m), 2.22 (2H, m), 2.54+2.67 (1H, 2×m), 3.62 (1H, q, *J* 7.1, OCH_2CH_2O), 3.86 (3H, m, OCH_2CH_2O), 5.24 (1H, m, $=C\mathit{H}CH_3$) and 9.31+9.32 (1H, 2×s, O=CH); ^{13}C NMR (100 MHz, $CDCl_3$): δ 13.0, 13.2, 16.2, 23.4, 23.5, 24.6, 25.2, 33.4, 34.2, 35.4, 36.4, 46.9, 47.0, 50.5, 51.1, 63.1 ($O\mathit{C}H_2CH_2O$), 63.7 ($OCH_2\mathit{C}H_2O$), 111.0 (OCO), 111.1 (OCO), 117.2 ($=\mathit{C}HCH_3$), 117.6 ($=\mathit{C}HCH_3$), 136.9 ($\mathit{C}=CH$), 137.1 ($\mathit{C}=CH$), 202.4 (O=CH) and 202.6

(O=CH); HRMS (EI) *m/z* Calcd for $C_{14}H_{22}O_3$ (M^+): 238.15689. Found: 238.15734.

4.1.7. (*Z*)/(*E*)-8-Ethylidene-6-(3-methylbut-1-yn-3-yl)-1,4-dioxaspiro[4.5]decane 9a/9b. Potassium carbonate (1.30 g, 9.42 mmol) was added to a stirred solution of (*Z*)/(*E*)-8-ethylidene-6-(2-methylpropanal-2-yl)-1,4-dioxaspiro[4.5]decane **8a/8b** (1.50 g, 6.30 mmol) and dimethyl (1-diazo-2-oxopropyl)phosphonate (1.82 g, 9.48 mmol) in methanol (40 ml) at 25 °C. The mixture was stirred for 5 d and further portions (5×0.5 equiv) of both potassium carbonate (5×0.43 g) and dimethyl (1-diazo-2-oxopropyl)phosphonate (5×0.60 g) were added to the reaction mixture at regular intervals over this time period. The solvent was evaporated under reduced pressure and the residue was partitioned between diethyl ether (50 ml) and water (50 ml). The organic phase was separated and the aqueous phase was extracted with another portion of diethyl ether (50 ml). The combined organic phase was dried, filtered, and evaporated under reduced pressure to leave a crude residue, which was purified by column chromatography on silica using 10% diethyl ether in light petroleum as the eluent to give *8-ethylidene-6-(3-methylbut-1-yn-3-yl)-1,4-dioxaspiro[4.5]decane* **9** (1.19 g, 81%) as a pale yellow oil containing both (*Z*)- and (*E*)-isomers in a ratio of 2:1. IR ν_{max} (film)/cm^{-1} 2110 (C≡C) and 1427 (C=C); ^{1}H NMR (400 MHz, $CDCl_3$): δ 1.33–1.41 (7H, 1×m+4×s, (CH_3)$_2$CC*H*), 1.59 (3H, m, (=CHC*H*$_3$)), 1.71 (1H, m), 1.84 (1H, m), 1.90–2.28 (3H, overlapping m), 2.45 (1H, m), 2.90 (1H, m), 3.95–4.06 (4H, overlapping m, OCH_2CH_2O) and 5.21 (1H, m, =C*H*CH_3); ^{13}C NMR (100 MHz, $CDCl_3$): δ 13.0, 13.1, 24.7, 28.3, 28.4, 28.9, 30.2, 30.4, 33.4, 33.5, 34.1, 35.9, 36.9, 37.1, 51.4, 52.0, 63.5 (O*C*H_2CH_2O), 63.8 (O*C*H_2CH_2O), 63.9 (OCH_2*C*H_2O), 68.0 (≡CH), 68.1 (≡CH), 92.8 (C≡), 93.0 (C≡), 112.2 (OCO), 112.3 (OCO), 116.7 (=*C*HCH_3), 117.0 (=*C*HCH_3), 137.4 (*C*=CH) and 137.7 (*C*=CH); HRMS (EI) *m/z* Calcd for $C_{15}H_{22}O_2$ (M^+): 234.16198. Found: 234.16165. Also isolated from this reaction was the starting aldehyde **8a/8b** (0.14 g).

4.1.8. Hexacarbonyl((*Z*)/(*E*)-8-ethylidene-6-[μ-[(1,2-η:1,2-η)-3-methylbut-1-yn-3-yl]]-1,4-dioxaspiro[4.5]decane)-dicobalt-(Co–Co) 10a/10b. A solution of (*Z*)/(*E*)-8-ethylidene-6-(3-methylbut-1-yn-3-yl)-1,4-dioxaspiro[4.5]decane **9a/9b** (1.18 g, 5.04 mmol) in light petroleum (10 ml) was added to a stirred solution of octacarbonyldicobalt (1.78 g, 5.20 mmol) in light petroleum (40 ml) over a 5 min period at 25 °C. The mixture was stirred for 2 h before it was filtered through a pad of silica using 10% diethyl ether in light petroleum as the eluent. The filtrate was evaporated under reduced pressure to leave a crude residue, which was purified by column chromatography on silica using a 0–10% diethyl ether in light petroleum gradient as the eluent to give *hexacarbonyl((Z)/(E)-8-ethylidene-6-[μ-[(1,2-η:1,2-η)-3-methylbut-1-yn-3-yl]]-1,4-dioxaspiro[4.5]decane)dicobalt-(Co–Co)* **10** (2.60 g, 99%) as a red oil containing both (*Z*)- and (*E*)-isomers in a ratio of 2:1. IR ν_{max} (film)/cm^{-1} 2089 (C=O), 2013 (C=O), 1465 (C=C) and 1442 (C=C); ^{1}H NMR (400 MHz, $CDCl_3$): δ 0.88–1.44 (7H, m), 1.57–1.76 (4H, m), 1.85–1.99 (1H, m), 2.01–2.23 (2H, m), 2.39–2.53 (1H, m), 2.97 (1H, d, *J* 13.1), 4.02 (4H, m, OCH_2CH_2O), 5.20 (1H, m, =C*H*CH_3) and 6.17+6.22 (1H, 2×s, ≡CH); ^{13}C NMR (100 MHz, $CDCl_3$): δ 13.4, 13.7, 14.5, 22.8, 24.8, 28.3, 30.1, 30.2, 32.0, 32.2, 33.5, 34.6, 36.1, 37.0, 37.2, 42.1, 42.3, 52.2, 53.0, 63.3 (O*C*H_2CH_2O), 63.8 (OCH_2*C*H_2O), 75.5, 75.9, 113.2 (OCO), 113.4 (OCO), 116.8 (=*C*HCH_3), 117.4 (=*C*HCH_3), 137.4 (*C*=CH), 137.7 (*C*=CH) and 200.8 (CO); HRMS (EI) *m/z* Calcd for $C_{20}H_{22}Co_2O_7$ (M^+−CO): 492.00295. Found: 492.00162.

4.1.9. Cyclopentenones 11a and 11b. A solution of hexacarbonyl((*Z*)/(*E*)-8-ethylidene-6-[μ-[(1,2-η:1,2-η)-3-methylbut-1-yn-3-yl]]-1,4-dioxaspiro[4.5]decane)dicobalt-(Co–Co) **10a/10b** (2:1) (188.0 mg, 0.36 mmol) and *n*-butyl methyl sulfide (0.16 g, 1.54 mmol) in 1,2-dichloroethane (5 ml) was heated under reflux for 30 min. The black mixture was then filtered through a pad of silica using diethyl ether as the eluent. The filtrate was evaporated under reduced pressure to leave a crude residue, which was purified by column chromatography on silica using a 0–50% diethyl ether in light petroleum gradient as the eluent to give *cyclopentenones* **11a** and **11b** (90.0 mg, 95% combined) as a 2:1 mixture (by proton-NMR). Compounds **11a** and **11b** were subsequently separated by column chromatography on silica using a 0–30% diethyl ether in light petroleum gradient as the eluent. This afforded **11a** (59.0 mg) and **11b** (31.0 mg) as colourless crystalline solids.

Analytical data for **11a** are as follows: mp 90–91 °C; IR ν_{max} (film)/cm^{-1} 3042 (vinyl C–H), 2978, 2927, 2876, 1702 (C=O) and 1625 (C=C); ^{1}H NMR (400 MHz, $CDCl_3$): δ 0.99 (3H, d, *J* 7.5, CHC*H*$_3$), 1.17 (3H, s, (C*H*$_3$)$_2$C), 1.28 (1H, m), 1.47 (3H, s, (CH_3)$_2$C), 1.70–2.03 (6H, overlapping m), 2.18 (1H, q, *J* 7.5, C*H*CH_3), 3.82 (1H, m, OCH_2CH_2O), 3.91 (2H, m, OCH_2CH_2O), 3.98 (1H, m, OCH_2CH_2O) and 5.70 (1H, s, C*H*=C); ^{13}C NMR (100 MHz, $CDCl_3$): δ 14.9 (CH*C*H$_3$), 22.8 ((*C*H$_3$)$_2$C), 31.8, 32.7, 32.9 ((*C*H$_3$)$_2$C), 39.3, 42.5 ((CH_3)$_2$*C*), 52.7 (*C*HCH_3), 55.8 (*C*CHCH_2), 57.2 (CH_2*C*CHCH_3), 63.7 (O*C*H_2CH_2O), 65.0 (OCH_2*C*H_2O), 110.2 (OCO), 119.8 (*C*H=C), 201.3 (CH=*C*) and 213.8 (C=O); HRMS (EI) *m/z* Calcd for $C_{16}H_{22}O_3$ (M^+): 262.15689. Found: 262.15650. Single crystals of cyclopentenone **11a** were obtained from diethyl ether/light petroleum, mounted in an inert oil, and transferred to the cold gas stream of the diffractometer. *Crystal data*. $C_{16}H_{22}O_3$, M=262.16, monoclinic, a=6.0402(13), b=31.423(4), c=7.7111(13) Å, β=107.469(15)°, U=1396.1(4) Å^3, T=295 K, space group $P2_1/n$ (no. 14), Z=4, μ(Mo Kα)=0.085 mm^{-1}, 2977 reflections measured, 2721 unique (R_{int}=0.0609), which were used in all calculations. Final $R1$=0.0481. The final $wR(F^2)$ was 0.1418 (all data). See Ref. 12 for full crystal data.

Analytical data for **11b** are as follows: mp 87–88 °C; IR ν_{max} (film)/cm^{-1} 3039 (vinyl C–H), 2966, 2940, 2883, 1702 (C=O), 1625 (C=C), 1453, 1370, 1108 and 1095; ^{1}H NMR (400 MHz, $CDCl_3$): δ 1.07 (3H, d, *J* 7.2, CHC*H*$_3$), 1.15 (1H, m), 1.19 (3H, s, (C*H*$_3$)$_2$C), 1.47 (3H, s, (C*H*$_3$)$_2$C), 1.71–1.86 (4H, overlapping m), 1.97 (1H, d, *J* 5.0, CC*H*CH_2), 2.22 (1H, d, *J* 11.8), 2.27 (1H, q, *J* 7.2, C*H*CH_3), 3.83 (1H, m, OCH_2CH_2O), 3.91 (2H, m, OCH_2CH_2O), 4.00 (1H, m, OCH_2CH_2O) and 5.80 (1H, s, C*H*=C); ^{13}C NMR (100 MHz, $CDCl_3$): δ 9.0 (CH*C*H$_3$), 22.8 ((*C*H$_3$)$_2$C), 31.2, 33.0 ((*C*H$_3$)$_2$C), 33.9 (C*C*H$_2$CH$_2$), 38.0, 42.5 ((CH_3)$_2$*C*), 55.2 (*C*HCH_3), 56.5 (*C*CHCH_2), 56.7 (CH_2*C*CHCH_3), 63.7 (O*C*H_2CH_2O), 65.0 (OCH_2*C*H_2O), 110.2 (OCO), 121.1 (*C*H=C), 200.5 (CH=*C*) and 211.6 (C=O); HRMS (EI) *m/z* Calcd for $C_{16}H_{22}O_3$ (M^+): 262.15689. Found: 262.15698. Single crystals of cyclopentenone **11b** were obtained from diethyl ether/light petroleum, mounted in an inert oil, and transferred to the cold gas stream of the diffractometer. *Crystal data*. $C_{16}H_{22}O_3$, $M=262.16$, monoclinic, $a=6.069(3)$, $b=16.253(5)$, $c=14.087(3)$ Å, $\beta=93.40(3)°$, $U=1387.1(7)$ Å^3, $T=123$ K, space group $P2_1/n$ (no. 14), $Z=4$, μ(Mo Kα)=0.085 mm^{-1}, 3105 reflections measured, 2835 unique ($R_{int}=0.032$), which were used in all calculations. Final $R1=0.067$. The final $wR(F^2)$ was 0.084 (all data). See Ref. 12 for full crystal data.

4.1.10. Alternative preparations of cyclopentenones 11a and 11b.

4.1.10.1. Use of trimethylamine *N*-oxide. Trimethylamine *N*-oxide dihydrate (0.18 g, 1.62 mmol) was added to a stirred solution of hexacarbonyl((*Z*)/(*E*)-8-ethylidene-6-[μ-[(1,2-η:1,2-η)-3-methylbut-1-yn-3-yl]]-1,4-dioxaspiro-[4.5]decane)dicobalt-(Co–Co) **10a/10b** (2:1) (95.0 mg, 0.18 mmol) in acetone (3 ml) at 25 °C. The mixture was stirred for 16 h before it was filtered through a pad of silica using diethyl ether as the eluent. The filtrate was evaporated under reduced pressure to leave a crude residue, which was purified by column chromatography on silica using a 0–50% diethyl ether in light petroleum gradient as the eluent to give *cyclopentenones* **11a** and **11b** (43.0 mg, 91% combined) as a 2:1 mixture (by proton-NMR). Analytical data were as given above.

4.1.10.2. Use of *N*-methylmorpholine *N*-oxide. *N*-Methylmorpholine *N*-oxide monohydrate (0.20 g, 1.48 mmol) was added to a stirred solution of hexacarbonyl((*Z*)/(*E*)-8-ethylidene-6-[μ-[(1,2-η:1,2-η)-3-methylbut-1-yn-3-yl]]-1,4-dioxaspiro[4.5]decane)dicobalt-(Co–Co) **10a/10b** (2:1) (99.0 mg, 0.19 mmol) in dichloromethane (3 ml) at 25 °C. The mixture was stirred for 16 h before it was filtered through a pad of silica using diethyl ether as the eluent. The filtrate was evaporated under reduced pressure to leave a crude residue, which was purified by column chromatography on silica using a 0–50% diethyl ether in light petroleum gradient as the eluent to give *cyclopentenones* **11a** and **11b** (42.0 mg, 84% combined) as a 2:1 mixture (by proton-NMR). Analytical data were as given above.

4.1.10.3. Use of polymer-supported sulfide.[3i] A mixture of hexacarbonyl((*Z*)/(*E*)-8-ethylidene-6-[μ-[(1,2-η:1,2-η)-3-methylbut-1-yn-3-yl]]-1,4-dioxaspiro[4.5]decane)-dicobalt-(Co–Co) **10a/10b** (2:1) (54.0 mg, 0.10 mmol) and polymer-supported sulfide (1 mmol g^{-1}, 0.36 g, 0.36 mmol) in 1,2-dichloroethane (3 ml) was heated under reflux for 30 min. The mixture was then filtered through a pad of silica using diethyl ether as the eluent. The filtrate was evaporated under reduced pressure to leave a crude residue, which was purified by column chromatography on silica using a 0–50% diethyl ether in light petroleum gradient as the eluent to give *cyclopentenones* **11a** and **11b** (21.0 mg, 80% combined) as a 2:1 mixture (by proton-NMR). Analytical data were as given above.

4.1.11. Methyl 2-(1,4-dioxaspiro[4.5]decan-8-on-6-yl)-2-methylpropanoate 12 and methyl 2-(8-((trimethylsilyl)oxy)-1,4-dioxaspiro[4.5]dec-7-ene-6-yl)-2-methylpropanoate 13.

Ytterbium(III) trifluromethanesulfonate trihydrate (20 mg, 0.03 mmol) was added to a stirred solution of 1,4-dioxaspiro[4.5]dec-6-en-8-one **4** (50 mg, 0.32 mmol) and 1-methoxy-1-((trimethylsilyl)oxy)-2-methylpropene (87 mg, 0.50 mmol) in dichloromethane (5 ml) at 25 °C. Stirring was continued for a further 24 h before filtration through a pad of silica using diethyl ether as the eluent to give a crude residue. Separation was achieved using column chromatography eluting with diethyl ether/light petroleum (10–50% mixtures) yielding *methyl 2-(1,4-dioxaspiro[4.5]decan-8-on-6-yl)-2-methylpropanoate* **12** (55 mg, 67%) and *methyl 2-(8-((trimethylsilyl)oxy)-1,4-dioxaspiro-[4.5]dec-7-ene-6-yl)-2-methylpropanoate* **13** (24 mg, 23%).

Analytical data for **12** are as follows: Found: C, 61.06; H, 7.83. $C_{13}H_{20}O_5$ requires C, 60.96; H, 7.87%; mp 60.6–60.8 °C; IR ν_{max} (film)/cm^{-1} 1698 (C=O) and 1724 (C=O); ^{1}H NMR (400 MHz, $CDCl_3$): δ 1.12 (3H, s, CH_3C), 1.15 (3H, s, CH_3C), 1.71–1.79 (1H, m), 1.98–2.04 (1H, m), 2.37–2.41 (1H, m), 2.47–2.52 (1H, m), 2.53–2.71 (3H, overlapping m), 3.65 (3H, s, CH_3O) and 3.92–4.05 (4H, m, OCH_2CH_2O); ^{13}C NMR (100 MHz, $CDCl_3$): δ 19.7 (CH_3C), 27.3 (CH_3C), 33.6 (CH_2), 38.5 (CH_2), 40.0 (CH_2), 42.9 ($(CH_3)_2C$), 49.2 (CH), 52.0 (CH_3O), 63.9 (OCH_2CH_2O), 65.0 (OCH_2CH_2O), 109.7 (OCO), 178.3 (OC=O) and 210.3 (C=O); HRMS (ES$^+$) *m/z* Calcd for $C_{13}H_{21}O_5$ (M^++1): 257.1389. Found: 257.1386.

Analytical data for **13** are as follows: Found: C, 58.85; H, 8.56. $C_{16}H_{28}O_5Si$ requires C, 58.56; H, 8.60%; IR ν_{max} (film)/cm^{-1} 1668 (C=C) and 1724 (C=O); ^{1}H NMR (400 MHz, $CDCl_3$): δ 1.19 (9H, s, $(CH_3)_3Si$), 1.14 (3H, s, CH_3C), 1.17 (3H, s, CH_3C), 1.58–1.64 (1H, m), 1.89–1.97 (1H, m), 2.03–2.08 (1H, m), 2.27–2.37 (1H, m), 2.93–2.94 (1H, m), 3.65 (3H, s, CH_3O), 3.72–3.78 (2H, m, OCH_2CH_2O), 3.89–3.96 (2H, m, OCH_2CH_2O) and 4.76–4.78 (1H, m, C=CH); ^{13}C NMR (100 MHz, $CDCl_3$): δ 0.6 ($(CH_3)_3Si$), 20.0, 27.2, 28.4, 31.1, 44.3, 49.8, 51.8, 65.2, 101.8 (C=*C*H), 109.4 (OCO), 152.2 (*C*=CH) and 179.0 (OC=O); HRMS (ES$^+$) *m/z* Calcd for $C_{16}H_{29}O_5Si$ (M^++1): 329.1784. Found: 329.1789.

4.1.12. Methyl 2-(1,4-dioxaspiro[4.5]decan-8-on-6-yl)-2-methylpropanoate 12 by hydrolysis of methyl 2-(8-((trimethylsilyl)oxy)-1,4-dioxaspiro[4.5]dec-7-ene-6-yl)-2-methylpropanoate 13.

To a stirred solution of methyl 2-(8-((trimethylsilyl)oxy)-1,4-dioxaspiro[4.5]dec-7-ene-6-yl)-2-methylpropanoate **13** (0.44 g, 1.35 mmol) in diethyl ether (5 ml) aqueous oxalic acid (2% w/w, 5 ml) was added. Stirring was continued for 12 h before saturated aqueous sodium bicarbonate solution (5 ml) was added. Separation and evaporation under reduced pressure gave *methyl 2-(1,4-dioxaspiro[4.5]decan-8-on-6-yl)-2-methylpropanoate* **12** (0.34 g, 99%). Analytical data were as given above.

4.1.13. Methyl 2-((*Z*)/(*E*)-8-ethylidene-1,4-dioxaspiro-[4.5]decan-6-yl)-2-methylpropanoate 14a/14b.

To a stirred suspension of ethyltriphenylphosphonium bromide (87 mg, 0.234 mmol) in THF (4 ml) at room temperature, a standardised solution of *n*-butyllithium (1.94 M, 0.13 ml, 0.252 mmol) in hexane was added dropwise. Stirring of the resulting orange slurry was continued for 1 h before a solution of methyl 2-(1,4-dioxaspiro[4.5]decan-8-on-6-yl)-2-methylpropanoate **12** (50 mg, 0.195 mmol) in THF (1 ml) was added. Stirring was continued for a further 16 h before evaporation of the solvent under reduced pressure. Diethyl ether (10 ml) was added before the slurry was sonicated in a cleaning bath for 2 min. Filtration through a pad of silica using diethyl ether as the eluent gave a crude residue, which was purified using column chromatography eluting with diethyl ether/light petroleum (0–40% mixtures). This gave *methyl 2-(8-ethylidene-1,4-dioxaspiro[4.5]decan-6-yl)-2-methylpropanoate* **14** (46 mg, 89%) as a mixture containing both (*Z*)- and (*E*)-isomers in a ratio of 1.6:1. This ratio was determined by the ^{1}H NMR integration of the signals at δ 2.57–2.59 and 2.60–2.61 ppm; from correlation and full assignment of both the ^{1}H and ^{13}C NMR spectra, these signals were identified as those relating to an allylic cyclohexyl H positioned *syn*- to the olefinic methyl group within the (*E*)- and (*Z*)-isomers, respectively. Found: C, 67.02; H, 9.06. $C_{15}H_{24}O_4$ requires C, 67.14; H, 9.01%; IR ν_{max} (film)/cm^{-1} 1443 ($C{=}C$) and 1730 ($C{=}O$); ^{1}H NMR (400 MHz, $CDCl_3$): δ 1.07–1.18 (m, 6H), 1.20–1.30 (m, 1H), 1.51 (t, 3H, *J* 6.5, $CH_3CH{=}C$), 1.70–1.88 (m, 1H), 1.89–1.91 (m, 1H), 2.08–2.11 (m, 0.61H), 2.12–2.22 (m, 2.39H), 2.57–2.59 (m, 0.39H), 2.60–2.61 (m, 0.61H), 3.75 (s, 3H, CH_3O), 3.76–3.91 (m, 4H, OCH_2CH_2O) and 5.12–5.20 (m, 1H, $CH_3CH{=}C$); ^{13}C NMR (100 MHz, $CDCl_3$): δ 13.4, 20.1, 25.0, 25.7, 27.7, 32.2, 33.2, 33.8, 34.7, 35.6, 36.6, 36.7, 42.9, 51.3, 51.8, 63.5, 64.6, 111.5, 117.1, 137.5 and 179.2; HRMS (ES$^+$) *m/z* Calcd for $C_{15}H_{25}O_4$ (M^++1): 269.1753. Found: 269.1752.

4.1.14. Alternative preparations of alkenes 14a and 14b.

4.1.14.1. Use of NaHMDS and ethyltriphenylphosphonium bromide. Using a similar procedure to that described in Section 4.1.13, with a standardised solution of sodium hexamethyldisilazide (0.273 M, 0.86 ml, 0.234 mmol) in THF, gave *methyl 2-(8-ethylidene-1,4-dioxaspiro[4.5]decan-6-yl)-2-methylpropanoate* **14** (40 mg, 77%) as a mixture containing both (*Z*)- and (*E*)-isomers in a ratio of 1:2.4.

4.1.14.2. Use of KHMDS and ethyltriphenylphosphonium bromide. Using a similar procedure to that described in Section 4.1.13, with a standardised solution of potassium hexamethyldisilazide (0.357 M, 0.67 ml, 0.239 mmol) in THF, gave *methyl 2-(8-ethylidene-1,4-dioxaspiro[4.5]decan-6-yl)-2-methylpropanoate* **14** (44 mg, 85%) as a mixture containing both (*Z*)- and (*E*)-isomers in a ratio of 1:2.3.

4.1.14.3. Use of KHMDS and ethyltriphenylphosphonium chloride. Using a similar procedure to that described in Section 4.1.13, with ethyltriphenylphosphonium chloride (76 mg, 0.234 mmol) and a standardised solution of potassium hexamethyldisilazide (0.357 M, 0.67 ml, 0.239 mmol) in THF, gave *methyl 2-(8-ethylidene-1,4-dioxaspiro[4.5]decan-6-yl)-2-methylpropanoate* **14** (41 mg, 79%) as a mixture containing both (*Z*)- and (*E*)-isomers in a ratio of 1:2.3.

4.1.14.4. Use of KHMDS and ethyltriphenylphosphonium iodide. Using a similar procedure to that described in Section 4.1.13, with ethyltriphenylphosphonium iodide (98 mg, 0.234 mmol) and a standardised solution of potassium hexamethyldisilazide (0.357 M, 0.67 ml, 0.239 mmol) in THF, gave *methyl 2-(8-ethylidene-1,4-dioxaspiro[4.5]decan-6-yl)-2-methylpropanoate* **14** (47 mg, 90%) as a mixture containing both (*Z*)- and (*E*)-isomers in a ratio of 1:2.3.

4.1.14.5. Use of NaHMDS and ethyltriphenylphosphonium chloride. Using a similar procedure to that described in Section 4.1.13, with ethyltriphenylphosphonium chloride (76 mg, 0.234 mmol) and a standardised solution of sodium hexamethyldisilazide (0.273 M, 0.86 ml, 0.234 mmol) in THF, gave *methyl 2-(8-ethylidene-1,4-dioxaspiro[4.5]decan-6-yl)-2-methylpropanoate* **14** (39 mg, 75%) as a mixture containing both (*Z*)- and (*E*)-isomers in a ratio of 1:2.5.

4.1.14.6. Use of NaHMDS and tetraethylphosphonium bromide. Using a similar procedure to that described in Section 4.1.13, with tetraethylphosphonium bromide (53 mg, 0.234 mmol), a standardised solution of sodium hexamethyldisilazide (0.273 M, 0.86 ml, 0.234 mmol) in THF, and sonication for 5 min on reaction work-up, gave *methyl 2-(8-ethylidene-1,4-dioxaspiro[4.5]decan-6-yl)-2-methylpropanoate* **14** (39 mg, 75%) as a mixture containing both (*Z*)- and (*E*)-isomers in a ratio of 1:1.1.

4.1.14.7. Use of KHMDS and tetraethylphosphonium bromide. Using a similar procedure to that described in Section 4.1.13, with tetraethylphosphonium bromide (53 mg, 0.234 mmol), a standardised solution of potassium hexamethyldisilazide (0.357 M, 0.67 ml, 0.239 mmol) in THF, and sonication for 5 min on reaction work-up, gave *methyl 2-(8-ethylidene-1,4-dioxaspiro[4.5]decan-6-yl)-2-methylpropanoate* **14** (39 mg, 75%) as a mixture containing both (*Z*)- and (*E*)-isomers in a ratio of 1:1.1.

4.1.15. (*Z*)/(*E*)-8-Ethylidene-6-(2-methylpropan-1-ol-2-yl)-1,4-dioxaspiro[4.5]decane 7a/7b from reduction of methyl 2-((*Z*)/(*E*)-8-ethylidene-1,4-dioxaspiro[4.5]decan-6-yl)-2-methylpropanoate 14a/14b. To a stirred solution of methyl 2-((*Z*)/(*E*)-8-ethylidene-1,4-dioxaspiro[4.5]decan-6-yl)-2-methylpropanoate **14a/14b** (1:2.4) (35 mg, 0.137 mmol) in diethyl ether (5 ml) at room temperature, lithium aluminium hydride (6 mg, 0.15 mmol) was added as a powder. Stirring of the grey emulsion was continued for 1 h at room temperature before water (0.1 ml) was added. Stirring was continued for a further 5 min before addition of aqueous sodium hydroxide solution (10% w/w, 0.1 ml). Finally, water (0.3 ml) was added and the resulting granular precipitate removed by filtration through Celite using diethyl ether as the eluent. Water (30 ml) was added to the filtrate and the organic phase was separated and dried over sodium sulfate to give *8-ethylidene-6-(2-methylpropan-1-ol-2-yl)-1,4-dioxaspiro[4.5]decane* **7a/7b** (32 mg, 97%) as a mixture containing both (*Z*)- and (*E*)-isomers in a ratio of 1:2.4. This ratio was determined by ^{1}H NMR integration as shown below. IR ν_{max} (film)/cm^{-1} 3489 (O–H) and 1440 ($C{=}C$); ^{1}H NMR (400 MHz, $CDCl_3$): δ 0.83 (2.13H, s, CH_3), 0.87 (0.87H, s, CH_3), 1.01 (2.13H, s, CH_3), 1.05 (0.87H, s, CH_3), 1.27–1.35 (1H, m), 1.58–1.64 (3H, m), 1.70–1.78 (1H, m), 1.86–1.95 (2H, m), 2.08–2.09 (0.29H, m), 2.15–2.24 (1.71H, overlapping m), 2.47–2.48 (0.29H, m), 2.71–2.74 (0.71H, m), 3.08–3.14 (1H, m), 3.34–3.40 (1H, m), 3.53–3.59 (1H, m), 3.88–4.02 (4H, m) and 5.19–5.24 (1H, m, $=CHCH_3$); ^{13}C NMR (100 MHz, $CDCl_3$): δ 12.8, 13.1, 22.0, 22.1, 24.6, 27.3, 27.5, 27.6, 33.3, 35.3, 36.1, 36.4, 38.4, 38.6, 47.8, 48.4, 63.0 (OCH_2CH_2O), 63.4 (OCH_2CH_2O), 71.8 (CH_2OH), 112.9 (OCO), 116.2 ($=CHCH_3$), 116.5 ($=CHCH_3$), 137.8 ($C{=}CH$) and 138.0 ($C{=}CH$).

4.1.16. Cyclopentenone 11b by epimerisation of cyclopentenone 11a. Cyclopentenone **11a** (25 mg, 0.095 mmol) was treated with lithium hydroxide (11.5 mg, 0.48 mmol) in THF (5 ml) and water (1 ml) at reflux for 3 d. This mixture was then extracted with diethyl ether and the organic phase washed with water before drying over sodium sulfate. This gave a mixture of cyclopentenones **11a** and **11b** in a ratio of 1:9 by ^{1}H NMR integration of the signals at δ 5.70 and 5.80 ppm. Separation of **11a** and **11b** was then achieved as described in Section 4.1.9.

4.1.17. Cyclopentanone 16. Palladium on charcoal (10%, 30 mg) was added to a solution of cyclopentenone **11b** (365.0 mg, 1.39 mmol) in toluene (20 ml). The mixture was placed under 45 psi of hydrogen gas and agitated using a Cook apparatus for 3 h. The mixture was then filtered through a pad of silica using diethyl ether as the eluent. The filtrate was evaporated under reduced pressure to give *cyclopentanone* **16** (365.0 mg, 99%) as a colourless crystalline solid, mp 44–45 °C; IR ν_{max} (film)/cm^{-1} 2959, 2921, 2876, 1704 ($\mathrm{C{=}O}$), 1459 and 1363; ^{1}H NMR (400 MHz, $\mathrm{CDCl_3}$): δ 0.95 (3H, d, J 7.6, $\mathrm{CHC}H_3$), 0.96 (3H, s, $(\mathrm{C}H_3)_2\mathrm{C}$), 1.22 (3H, s, $(\mathrm{C}H_3)_2\mathrm{C}$), 1.52 (2H, overlapping m), 1.62–1.69 (2H, overlapping m), 1.75 (1H, m), 1.83–1.94 (2H, m), 2.03 (1H, dt, J 8.6 and 1.2), 2.14 (1H, q, J 7.6, $\mathrm{C}H\mathrm{CH_3}$), 2.24 (1H, ddd, J 18.2, 6.9 and 1.5, $\mathrm{O{=}CC}H_2\mathrm{CH}$), 2.34 (1H, dd, J 18.1 and 10.8, $\mathrm{O{=}CC}H_2\mathrm{CH}$), 3.76–3.89 (3H, overlapping m, $\mathrm{OCH_2CH_2O}$) and 3.96 (1H, m, $\mathrm{OCH_2CH_2O}$); ^{13}C NMR (100 MHz, $\mathrm{CDCl_3}$): δ 11.8 ($\mathrm{CH}C\mathrm{H_3}$), 26.7 ($((\mathrm{CH_3})_2\mathrm{C})$), 29.2 ($((C\mathrm{H_3})_2\mathrm{C})$), 30.5, 31.3, 38.3 ($\mathrm{O{=}C}C\mathrm{H_2CH}$), 41.9 ($((\mathrm{CH_3})_2C)$), 42.2 ($\mathrm{C}C\mathrm{H_2CH}$), 49.4 ($\mathrm{CH_2}C\mathrm{CHCH_3}$), 49.5 ($\mathrm{O{=}CCH_2}C\mathrm{H}$), 50.9 ($C\mathrm{HCH_3}$), 56.2 ($\mathrm{C}C\mathrm{HCH_2}$), 63.4 ($\mathrm{O}C\mathrm{H_2CH_2O}$), 64.8 ($\mathrm{OCH_2}C\mathrm{H_2O}$), 111.0 (OCO) and 221.4 ($\mathrm{C{=}O}$); HRMS (EI) m/z Calcd for $\mathrm{C_{16}H_{24}O_3}$ ($\mathrm{M^+}$): 264.17254. Found: 264.17280. Single crystals of ketone **16** were obtained from diethyl ether/light petroleum, mounted in an inert oil, and transferred to the cold gas stream of the diffractometer. *Crystal data*. $\mathrm{C_{16}H_{24}O_3}$, M=264.17, monoclinic, a=8.3280(3), b=8.3930(3), c=10.2120(4) Å, β=106.696(2)°, U=683.70(4) Å^3, T=150 K, space group $P2_1/n$ (no. 14), Z=2, μ(Mo Kα)=0.087 mm^{-1}, 5455 reflections measured, 3107 unique (R_{int}=0.0273), which were used in all calculations. Final $R1$=0.0340. The final $wR(F^2)$ was 0.0825 (all data). See Ref. 12 for full crystal data.

4.1.18. Cyclopentanol 17. Lithium aluminium hydride (37.0 mg, 0.97 mmol) was added to a stirred solution of cyclopentanone **16** (260.0 mg, 0.985 mmol) in diethyl ether (20 ml) at 0 °C. The mixture was stirred for 2 h before it was allowed to warm to 25 °C and the reaction was quenched by the addition of water (0.04 ml) then 10% aqueous sodium hydroxide solution (0.04 ml) and, lastly, another portion of water (0.12 ml). This resulted in a white granular precipitate, which was removed by filtration through a pad of silica using diethyl ether as the eluent. The filtrate was evaporated under reduced pressure to give *cyclopentanol* **17** (259 mg, 99%) as a colourless crystalline solid, mp 75–85 °C; IR ν_{max} (film)/cm^{-1} 3317 (O–H), 2959, 2889, 1459, 1376, 1114 and 1051; ^{1}H NMR (400 MHz, $\mathrm{CDCl_3}$): δ 0.94 (3H, d, J 7.0, $\mathrm{CHC}H_3$), 0.98 (3H, s, $(\mathrm{C}H_3)_2\mathrm{C}$), 1.18 (3H, s, $(\mathrm{C}H_3)_2\mathrm{C}$), 1.28–1.52 (4H, overlapping m), 1.63–1.93 (8H, overlapping m), 3.57 (1H, m, $\mathrm{C}H\mathrm{OH}$), 3.75–3.87 (3H, overlapping m, $\mathrm{OCH_2CH_2O}$) and 3.95 (1H, m, $\mathrm{OCH_2CH_2O}$); ^{13}C NMR (100 MHz, $\mathrm{CDCl_3}$): δ 12.4 ($\mathrm{CH}C\mathrm{H_3}$), 26.5 ($((C\mathrm{H_3})_2\mathrm{C})$), 28.7 ($((C\mathrm{H_3})_2\mathrm{C})$), 30.6, 31.9, 35.6 ($\mathrm{HOCH}C\mathrm{H_2CH}$), 40.7 ($((\mathrm{CH_3})_2C)$), 42.8, 50.2 ($\mathrm{CH_2}C\mathrm{CHCH_3}$), 50.4 ($C\mathrm{HCH_3}$), 52.6 ($\mathrm{HOCHCH_2}C\mathrm{H}$), 57.9 ($\mathrm{C}C\mathrm{HCH_2}$), 63.3 ($\mathrm{O}C\mathrm{H_2CH_2O}$), 64.7 ($\mathrm{OCH_2}C\mathrm{H_2O}$), 81.5 (HOCH) and 111.8 (OCO); HRMS (EI) m/z Calcd for $\mathrm{C_{16}H_{26}O_3}$ ($\mathrm{M^+}$): 266.18819. Found: 266.18727.

4.1.19. Xanthate ester 18. A solution of *n*-butyllithium in hexanes (2.5 M, 0.30 ml, 0.75 mmol) was added over a 5 min period to a stirred solution of cyclopentanol **17** (187.0 mg, 0.703 mmol) in tetrahydrofuran (5 ml) at 0 °C. The mixture was stirred for 5 min before carbon disulfide (85.0 mg, 0.067 ml, 1.12 mmol) was added and the mixture was allowed to warm to 25 °C. The mixture was stirred for 80 min before the reaction was quenched by the addition of methyl iodide (0.12 g, 0.052 ml, 0.84 mmol) and then stirred for a further 30 min. The mixture was then partitioned between diethyl ether (30 ml) and water (30 ml), the organic phase separated, and the aqueous phase extracted with another portion of diethyl ether (30 ml). The combined organic phase was dried, filtered, and evaporated under reduced pressure to leave a crude residue, which was purified by column chromatography on silica using a 0–30% diethyl ether in light petroleum gradient as the eluent. This gave *xanthate ester* **18** (235.0 mg, 94%) as a pale yellow oil, which was characterised by infrared and NMR spectroscopy and was then used immediately in the next synthetic step. IR ν_{max} (film)/cm^{-1} 2966, 1485, 1376, 1223 and 1057; ^{1}H NMR (400 MHz, $\mathrm{CDCl_3}$): δ 0.94 (3H, d, J 7.2, $\mathrm{CHC}H_3$), 1.01 (3H, s, $(\mathrm{C}H_3)_2\mathrm{C}$), 1.20 (3H, s, $(\mathrm{C}H_3)_2\mathrm{C}$), 1.47–1.57 (3H, m), 1.68–1.92 (6H, overlapping m), 2.06 (1H, m), 2.23 (1H, m), 2.55 (3H, s, $\mathrm{CH_3S}$), 3.79–3.90 (3H, overlapping m, $\mathrm{OCH_2CH_2O}$), 3.97 (1H, m, $\mathrm{OCH_2CH_2O}$) and 5.37 (1H, m, $\mathrm{C}H\mathrm{OC{=}S}$); ^{13}C NMR (100 MHz, $\mathrm{CDCl_3}$): δ 12.9, 19.0, 26.6, 28.7, 31.9, 32.0, 32.8, 41.3, 42.5, 46.9, 50.0, 52.8, 58.0, 63.8 ($\mathrm{O}C\mathrm{H_2CH_2O}$), 65.2 ($\mathrm{OCH_2}C\mathrm{H_2O}$), 92.1 ($C\mathrm{HOC{=}S}$), 111.5 (OCO) and 216.2 ($\mathrm{OC{=}S}$).

4.1.20. Acetal 19. A solution of xanthate ester **18** (45.0 mg, 0.126 mmol), tri-*n*-butyltin hydride (0.50 g, 1.71 mmol) and AIBN (13.0 mg, 0.08 mmol) in deoxygenated benzene (20 ml) was heated under reflux for 48 h. The solvent was evaporated under reduced pressure to leave a crude residue, which was purified by column chromatography on silica using a 0–20% diethyl ether in light petroleum gradient as the eluent to give *acetal* **19** (24.0 mg, 76%) as a colourless oil. IR ν_{max} (film)/cm^{-1} 2959, 2876, 1472, 1363 and 1102; ^{1}H NMR (400 MHz, $\mathrm{CDCl_3}$): δ 0.84 (3H, d, J 7.1, $\mathrm{CHC}H_3$), 0.97 (3H, s, $(\mathrm{C}H_3)_2\mathrm{C}$), 1.17 (3H, s, $(\mathrm{C}H_3)_2\mathrm{C}$), 1.24–1.90 (13H, overlapping m), 3.78–3.90 (3H, overlapping m, $\mathrm{OCH_2CH_2O}$) and 3.97 (1H, m, $\mathrm{OCH_2CH_2O}$); ^{13}C NMR (100 MHz, $\mathrm{CDCl_3}$): δ 15.7 ($\mathrm{CH}C\mathrm{H_3}$), 25.8, 26.9 ($((C\mathrm{H_3})_2\mathrm{C})$), 28.2 ($((C\mathrm{H_3})_2\mathrm{C})$), 31.4, 31.6, 37.3 ($C\mathrm{H_2CHCH_3}$), 41.6 ($((\mathrm{CH_3})_2C)$), 41.7, 41.8 ($C\mathrm{HCH_3}$), 53.6 ($\mathrm{CH_2}C\mathrm{CHCH_3}$), 56.7 ($\mathrm{CH_2CH_2}C\mathrm{HC}$), 58.1 ($\mathrm{C}C\mathrm{HCH_2}$), 63.4 ($\mathrm{O}C\mathrm{H_2CH_2O}$), 64.8 ($\mathrm{OCH_2}C\mathrm{H_2O}$) and 112.2 (OCO); HRMS (EI) m/z Calcd for $\mathrm{C_{16}H_{26}O_2}$ ($\mathrm{M^+}$): 250.19328. Found: 250.19432.

4.1.21. Cedrone 15.[2a,e] Triphenylphosphine (2.6 mg, 0.01 mmol) and carbon tetrabromide (3.3 mg, 0.01 mmol) were added to a stirred solution of acetal **19** (32.0 mg, 0.13 mmol) in acetone (5 ml) at 25 °C. The mixture was stirred for 1 h before the solvent was evaporated under reduced pressure to leave a crude residue, which was purified by column chromatography on silica using a 5–20% diethyl ether in light petroleum gradient as the eluent to give *cedrone* **15** (26.1 mg, 99%) as a colourless oil. IR $\nu_{\max}$ (film)/cm^{-1} 2960, 2877, 1715 and 1460; ^{1}H NMR (400 MHz, CDCl$_3$): δ 0.89 (3H, d, J 7.1, CHCH_3), 1.00 (3H, s, (CH_3)$_2$C), 1.01 (3H, s, (CH_3)$_2$C), 1.42 (1H, m), 1.51 (1H, m), 1.56–1.76 (4H, overlapping m), 1.80–2.00 (4H, overlapping m), 2.27–2.36 (2H, overlapping m, O=CCHCH$_2$+CH$_2$CH_2C=O) and 2.48 (1H, dd, J 18.3 and 7.8, CH$_2$CH_2C=O); ^{13}C NMR (100 MHz, CDCl$_3$): δ 15.7 (CHCH$_3$), 25.7, 26.0 ((CH$_3$)$_2$C), 26.4 ((CH$_3$)$_2$C), 32.1, 36.8, 37.0, 41.5, 41.8, 43.0 ((CH$_3$)$_2$$C$), 54.6 (CH$_2$$C$CHCH$_3$), 57.1 (CH$_2CH_2$$C$HC), 67.3 (O=C$CHCH_2$) and 214.4 (C=O); HRMS (EI) *m/z* Calcd for $C_{14}H_{22}O$ (M$^+$): 206.16707. Found: 206.16753.

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