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SYSTEM ORIENTED DESIGN OF TRIQUINANES: STEREOCONTROLLED SYNTHESIS OF PENTALENIC ACID AND PENTALENENE[1,2]

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Abstract: Pentalenic acid, **5**, and pentalenene, **4**, and their C-9 epimers **5a** and **4a**, respectively, were synthesized using [4+1] and [2+3] cyclopentene annulation methodology. The key steps involved internal cyclopropanation of dienes **23** or cyclopropanation of enone **25** followed by the thermolytic rearrangements of cyclopropanes **24**, **39**, **42**, **45**, and **48** to furnish triquinanes **26** and **40**. An investigation of electronic effects affecting the diradical cleavage of vinylcyclopropanes was performed. The triquinanes **26** or **40** were transformed to the title compounds by reductive operations at C-9. The equilibration of esters **60** at C-9 was briefly addressed in the context of molecular mechanics predictions regarding the thermodynamic stabilities of conformations at C-9 in the natural vs. the epi series. The stereoselectivities in approaches to natural hydrocarbons and their C-9 epimers were evaluated as better than 9:1 in each series.

Introduction

Fifteen years ago the first natural product containing a triquinane nucleus was isolated by Shibata and named retigeranic acid, **11** (Fig. 1).[4] Since that time over eighty triquinanes have been identified from natural sources and classified as either linear or nonlinear (angular), depending on thez topology of the ring fusion.[5] These compounds have attracted intense attention of the chemical community as pleasing targets for synthetic[6-19] and biosynthetic studies.[20] Since many of them were shown to possess significant biological activities ranging from simple antibiotic action to antitumor properties,[21] the immense effort aimed at their total syntheses is justified. The biologically most important terpenes are found in the hirsutane (linear) and pentalenane (angular) families of compounds. Not surprisingly, the synthetic efforts have frequently been directed at generalized approaches to either class of compounds. Some of the terpenes relevant to the discussion are portrayed in Fig. 1.

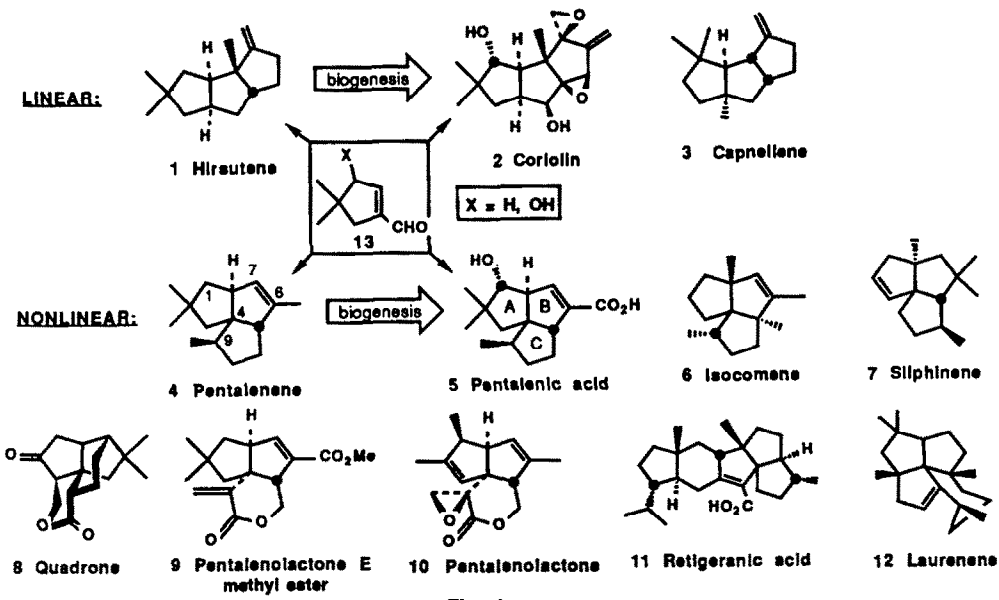

Fig. 1

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Strategies of some generality for the syntheses of triquinanes have been advanced by Paquette,[22] Crimmins,[23] Sternbach,[24] Curran,[25] Cook,[26] Little,[27] Wender,[28] Greene,[29] Mehta,[30] and Hudlicky,[31] but few, if any, of these were aimed at the synthesis of all triquinane sesquiterpenes.[32] A truly general strategy would therefore have to take into account any existing substitution pattern as well as any pattern likely to be isolated at a future time. Our efforts have been directed toward such a general strategy of triquinane synthesis.[12j,15h,34,43,44,48]

We noted that all of the triquinanes are related through a single common denominator---at least one of the cyclopentane rings possesses, at a minimum, a 1,2,3-trisubstitution pattern. This observation was translated into a general system-oriented design of such a ring in the context of the overall topology of both classes of triquinanes via the [4+1] annulation of dienic diazo ketones, Fig. 2. This strategy, representing a formal 1,4 addition to a diene, satisfied the requirements of producing the appropriately substituted cyclopentane.

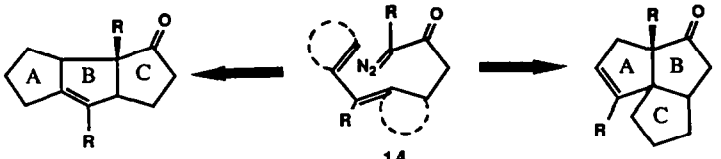


Fig. 2

This approach dictated that a fully general method for a rapid preparation of any dienic diazo ketone of type **14** in which the diene was located either exo (nonlinear topology) or endo (linear) to any existing rings be developed. Successful solutions to this problem have been realized by the application of a regioselective Claisen rearrangement (endo and exo dienes) or a vinylogous Reformatsky reaction (exo dienes). Applications of these methods have been published in several synthetic approaches to triquinane natural products.[2b,12j,15h,40,44]

We also noted an interesting topographical relationship with respect to ring-A oxygenation in that hirsutene and pentalenene are the biogenetic progenitors of the more highly oxidized terpenes coriolin and pentalenic acid, respectively. Therefore a single starting material could be used in the synthesis of all four sesquiterpenes provided the state of oxidation in ring A could be manipulated at will and provided the aforementioned methodology for the synthesis of exo and endo dienes would be used. Additionally, almost all of the compounds in the pentalenolactone family could become available by manipulations of a penultimate precursor, triquinane **26**, in which all rings bear a functional group (see Conclusion). The success of this approach along with the practical delineation of the key reactions in this sequence have formed the basis of our undertaking. In this manuscript we describe efficient syntheses for pentalenene and pentalenic acid, and their C-9 epimers.

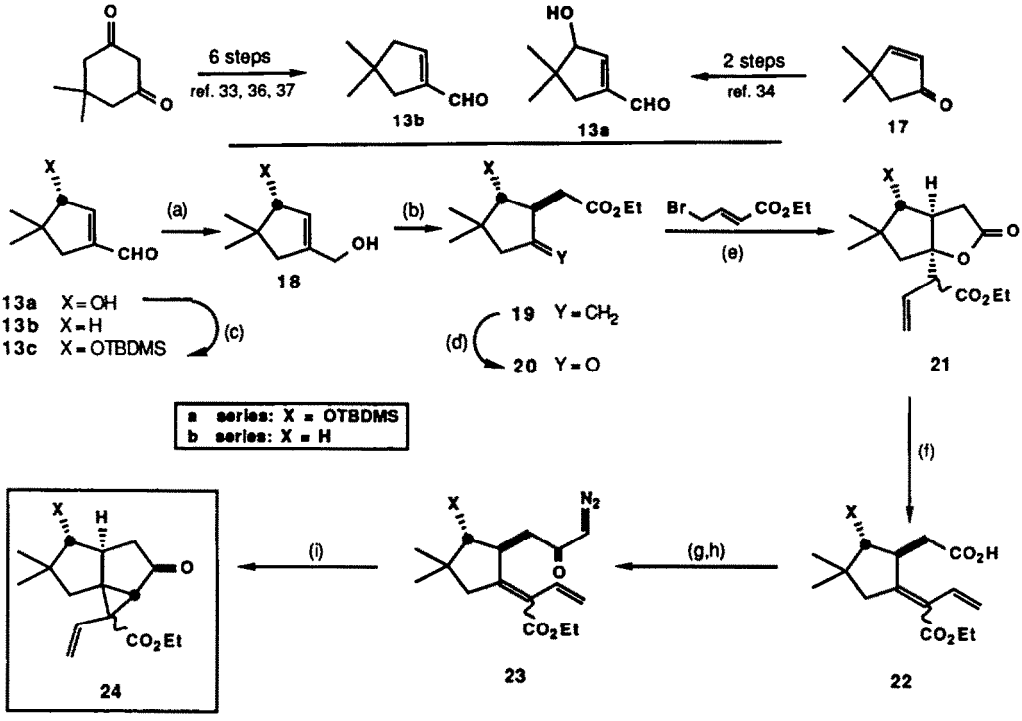
Results and Discussion

Preparation of Vinylcyclopropanes. The synthesis of pentalenic acid was modeled after the successful preparation of pentalenene[2b] except for the choice of starting materials and the final functionalization of triquinanes **26** or **40**. The starting material in the pentalenene synthesis was the aldehyde **13b**, Scheme 1, whose six step preparation from dimedone has been published.[33] Its oxygenated cousin, aldehyde **13a**[34], was prepared easily from enone **17**[35] in a short sequence of reactions. Further improvements in the synthesis of **13b**, became available through experimental adjustments[36,37] and both compounds could be prepared on a scale of several hundred grams in excellent overall yields. Since the preparation of **13a** was shorter and less costly than that of **13b** we considered the reductive cleavage of the allylic hydroxyl in **13a** as an alternate source of **13b**, but saved the pursuit of this issue for the future generations of approaches to the pentalenane terpenes. Because of the similarities in the syntheses of pentalenic acid and pentalenene, the chemistry of the preparations will be discussed together, with relevant differences indicated in both the discussion and the experimental sections.

The protection of **13a** was accomplished with TBDMSCl to give **13c**. The reduction of aldehydes **13b** and **13c** gave allylic alcohols **18** (**18a**: 87%, **18b**: 91%), and these furnished, via ortho-ester Claisen rearrangement, the olefinic esters **19** (**19a**: 89%, 86:14 trans:cis, **19b**: 75%). The

ozonolysis of these materials provided excellent yields of keto esters **20** (**20a**: 83%; **20b**: 96%). The overall efficiency of this Claisen-ozonolysis procedure compares favorably with any alkylative approaches to 1,4 dicarbonyl compounds of this type.[38]

Exposure of these substrates to the organozinc reagent derived from ethyl 4-bromocrotonate under the conditions favoring the α-addition[39] (Zn (Cu)/EtO_2, trace of HOAc) gave excellent yields of lactones **21** (**21a**: 83%; **21b**: 86%) which provided dienic acids **22** (**22a**: 80%, **22b**: 79%) upon carefully controlled elimination with DBU (DME, RT, 1 h), Scheme 1. The acids were obtained as mixtures of E and Z isomers (**22a**, E:Z=3:2; **22b**, E:Z=2:1) and these ratios were found to be independent of the erythro/threo composition of lactones **21**. The elimination conditions for β-acetoxy or β-alkoxy esters were briefly studied for several compounds, but no rationale was found



Reagents: a) $NaBH_4$, b) $(EtO)_3CCH_3$ / H^+ / 200°C, c) TBDMSCl / imidazole / DMF, d) O_3 / CH_2Cl_2 / DMS, e) Zn/Cu(AcOH) / Et_2O, f) DBU / DME, g) $(COCl)_2$ / PhH, h) CH_2N_2 / Et_2O, i) $Cu(acac)_2$ / $CuSO_4$ / PhH

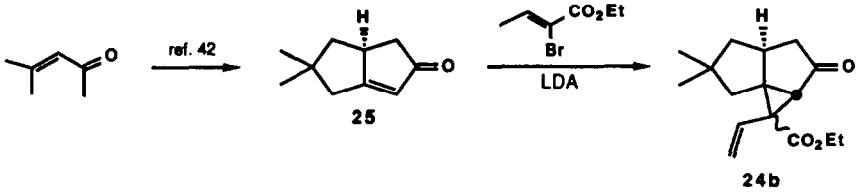
Scheme 1

for the origin of the steric scrambling.[40] The Reformatsky-elimination route thus provided the exo dienic acids **22** in an excellent manner satisfying the requirements of this general method of diene synthesis.

The acids **22** were converted to diazo ketones **23** via their acid chlorides and the vinylcyclopropanes were generated by the addition of dilute solutions of **23** in benzene to a refluxing slurry of anhydrous $CuSO_4$ and $Cu(acac)_2$ in benzene (**24a**: 45%, **24b**: 63%, overall from respective dienic acids). The E and Z ratios of acids **22** were propagated to the stage of vinylcyclopropanes **24** where they manifested themselves in the relative proportions of exo and endo isomers. Apart from the studies directed at the confirmation of steric homogeneity of the cyclopropanation process, the isomers were carried through as mixtures since the stereocenters converged at C-9 at the stage of triquinanes **26** and **40**. In the interest of experimental precision, analytical samples of erythro and threo lactones **21**, E and Z acids **22**, E and Z diazo ketones **23**, and exo and endo vinylcyclopropanes **24** were obtained and each series carried independently to triquinanes **26** or **40**, demonstrating such stereoconvergence. Any subsequent large scale preparations of these triquinanes were performed using mixtures of isomers.

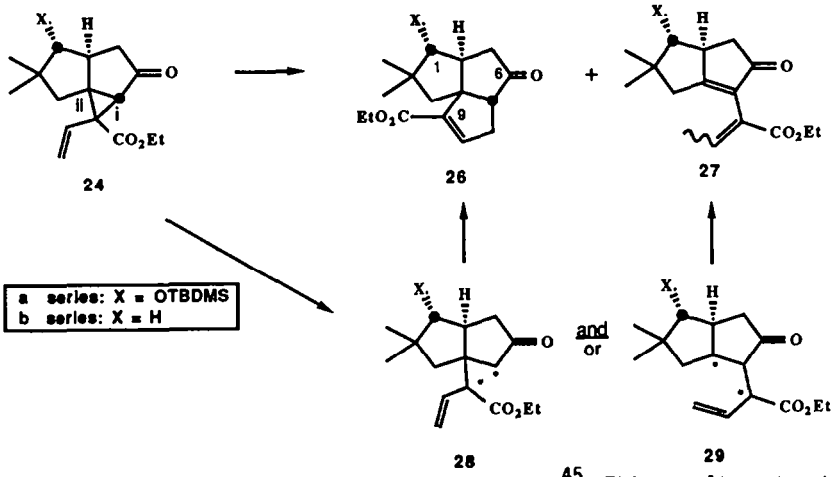
During the course of this work a new cyclopropanation methodology was discovered involving the additions of the dienolate derived from ethyl 2-bromocrotonate to enones.[41] Vinylcyclopropanes **24**

were prepared in a much shorter sequence from mesityl oxide via the cyclopropanation of the known enone **25**,[42] as shown. The stage was now set for the final transformations of vinylcyclopropanes to triquinanes via the vinylcyclopropane-cyclopentene rearrangement.[43]



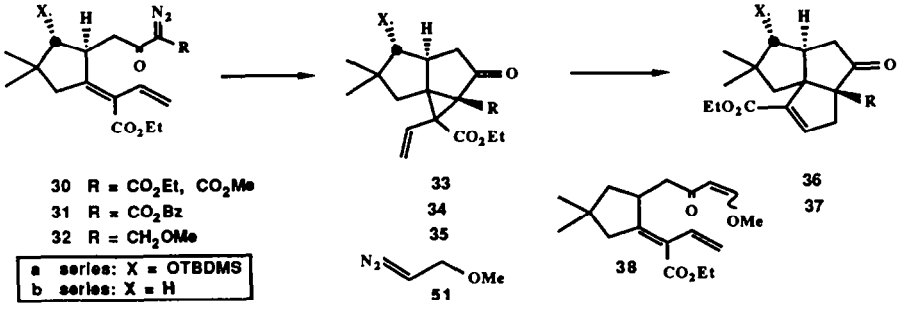
25 **24b**

Rearrangements of vinylcyclopropanes. Following well-established conditions of pyrolysis for these types of compounds,[44] we subjected cyclopropanes **24** to thermolysis at 585° through a $PbCO_3$-conditioned Vycor tube. To our surprise, we obtained only traces of desired triquinanes **26** and isolated enones **27** as major products. We rationalized these results by invoking the cleavage of



24 **26** **27** **28** **29**

bond **ii** in cyclopropanes **24** rather than a retro-ene type process.[45] This result contrasts with our previous experience in pyrolyzing over 40 diversely substituted cyclopropanes.[43,46,47,48] In most cases the bond **i** that is flanked by both vinyl group allylic radical) and a carbonyl (a pseudo-allylic radical) undergoes regioselective cleavage. We reasoned that, in the case of a secondary α-keto radical competing with a tertiary ring junction radical, the more substituted species predominates. In order to test the hypothesis of substitution, several derivatives of **24** were prepared and pyrolyzed. Since we have demonstrated that β-keto α-diazo esters lead to vinylcyclopropanes that cleave through bond **i** to give cyclopentenes,[47,48] we prepared diazo keto esters **30** and **31**[49,50] and the diazo ketone **32**.[51] In all cases the position α to the carbonyl would contain a removable substituent at C-5. For example, keto esters **36** and **37** could be hydrolyzed (hydrogenated) and decarboxylated while the putative triquinane, derived from **35**, containing methoxy methylene would suffer acid catalyzed retro-aldol process to free C-5.



30 R = CO_2Et, CO_2Me
31 R = CO_2Bz
32 R = CH_2OMe

33 **34** **35** **36** **37** **38**

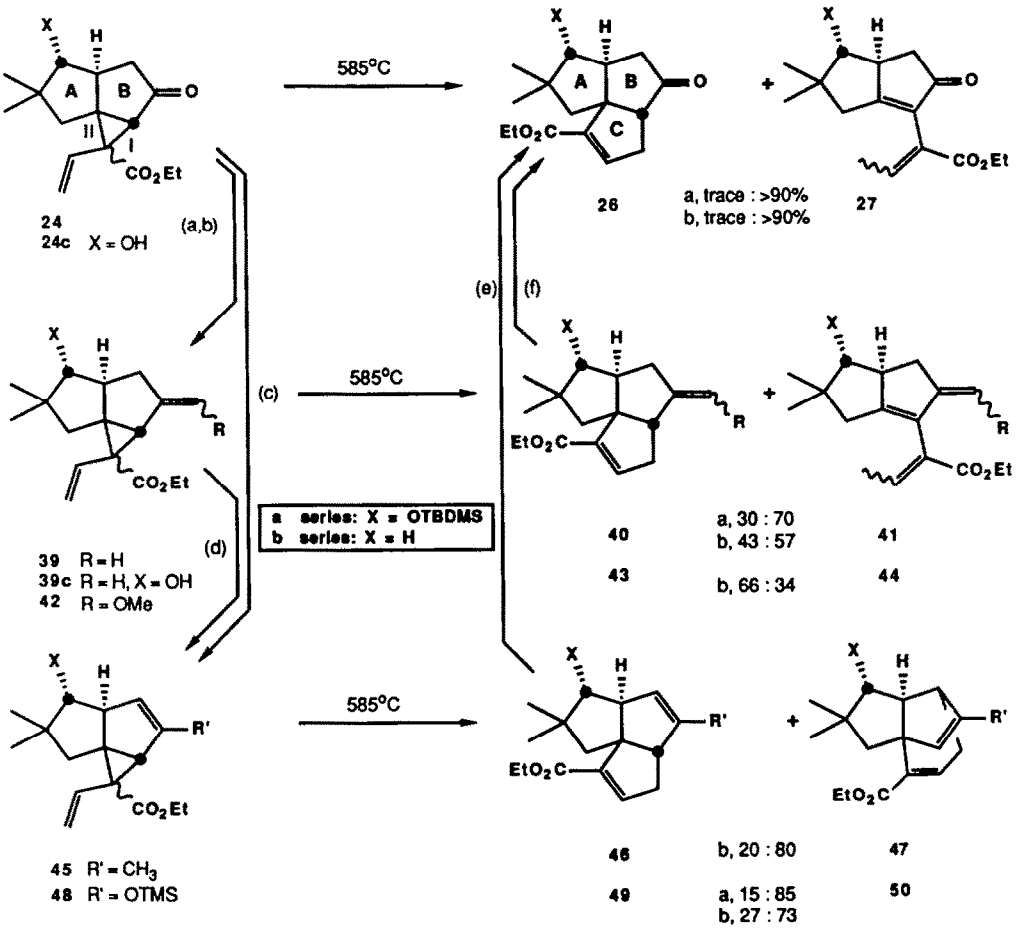
51

In both cases involving the keto esters only slightly improved yields of triquinanes **36** and **37** were obtained.[49,50] These results were again surprising and in sharp contrast to the course of rearrangement of the aforementioned cyclopropanes derived from keto esters of similar

structure.[47,48] The rearrangement of cyclopropane **35**, derived from the acid chloride of **22** by the use of a novel diazo alkane, 1-diazo-2-methoxyethane **51**,[52] could not be studied since diazo ketone **32** failed to cyclopropanate but rather gave the product of neighboring C-H bond insertion, enol ether **38**. This observation will prove useful as a new synthesis of enol ethers of β-keto aldehydes by homologation of carboxylic acid chlorides with reagent **51**.[53]

We next turned to investigations directed at increasing the electron content in the radical derived from cleavage of bond **i**. To this end exocyclic olefins **39a** and **39b** and the exocyclic enol ethers **42a** and **42b** were prepared and their tendency for rearrangement tested. Interestingly, in the pentalenic acid series, the Wittig reaction failed with **24a**, which had to be first converted to free alcohol **24c**. Dauben's modification of the Wittig reaction[62] was used to convert this material to **39c**, which was then protected to give **39a**. The olefins gave much improved yields of triquinanes (30% in the pentalenic acid series; 40% in the pentalenene series) but the major products were again the dienes **41a** and **41b**. The enol ether, however, because of the contribution of a heteroatom stabilizing the allylic radical, gave a 60% yield of tricyclic material **43**.[54] Presumably, the use of phenyl or benzyl enol ethers rather than methyl enol ethers would improve the yields further, but this supposition has not been tested. The resulting triquinanes **40** and **43** could be selectively ozonized to keto esters **26** to provide for an economic approach to this material. The exocyclic olefin **40** was used directly in the synthesis of the title compounds since during its preparation the final carbon necessary in the pentalenene series was incorporated via the Wittig reaction, Scheme **2**.[55]

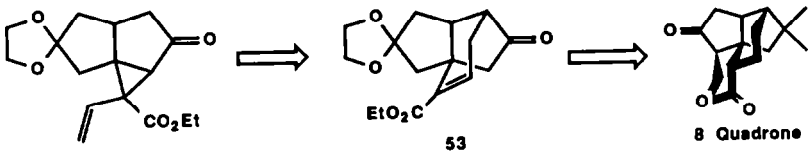
We thought that the tendency to form dienes of type **41** and **44** would diminish if the B-ring of



Reagents: a) R = H, Ph_3PCH_3Br / Am^{t}OK / Am^{t}OH / PhH, b) R = OMe, $CH_3OCH_2PPh_3Cl$ / Am^{t}OK / Am^{t}OH / PhH, c) R' = OTMS, TMSI / HMDS / pentane, d) R' = CH_3, p-TsOH / CH_2Cl_2, e) R' = OTMS, H^+, f) O_3 / CH_2Cl_2

Scheme 2

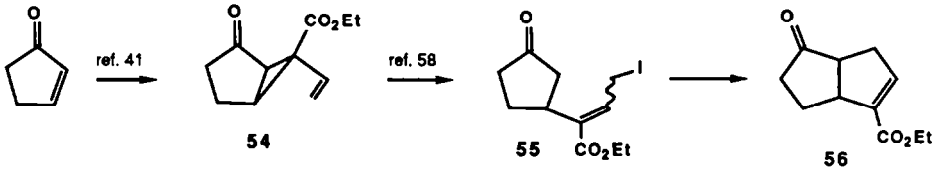
cyclopropanes already contained sp^2 hybridized centers, as in **45** or **48**. We anticipated that this ring would not accommodate two olefins because of the intense flattening of the remaining ring junction carbon. We prepared the endocyclic olefins **45a** and **45b** and the enol ethers **48a** and **48b**. Pyrolysis of the olefins **45** provided none of the dienes, and, as expected, furnished the triquinanes **46** in 20% yield.[54] In addition the bridged structures **47** were obtained in 80% yields, arising from the Cope rearrangement of the divinylcyclopropanes in **45**, a possibility precluded in the thermolyses of **39** by the anti-Bredt olefin that would form in the product.[56] A surprising result presented itself upon preparation of enol ethers **48**. The endo isomer rearranged to the bridged structure **50** at -78° to 0°C during its preparation (!), while the exo isomer required pyrolysis conditions for the rearrangement to occur. The rearrangements of the exo isomer thus gave 20% yields of triquinanes **49**, which were hydrolyzed to keto esters **26**, and 80% yield of the bridged compounds **50** (isolated as the ketones on workup), whereas the endo isomer gave only bridged tricycles **50**. It should be noted that the [3.2.1] systems generated in this way possess the carbon skeleton of quadrone **8**. In principle we could use this approach in the synthesis of quadrone type intermediate **53**.[57]



52 53

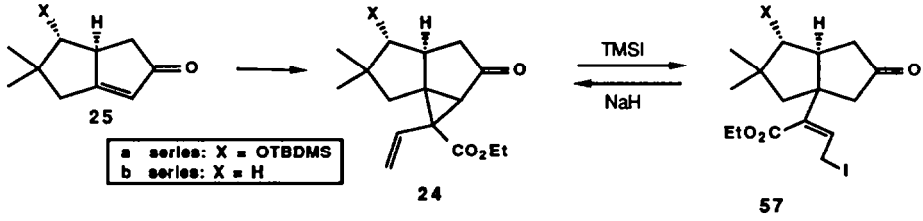
In summary, the investigation of electronic effects on the rearrangements of cyclopropanes **24**, **39**, **42**, **45**, and **48** revealed that increased electron content of the ring-B olefin favors the cyclopentene rearrangement. The formation of bicyclo[3.2.1]octane systems proved fortuitous and will be exploited appropriately in further applications to synthesis.[58]

Nucleophilic Opening of Vinylcyclopropanes as means of [2+3] Annulation. During the course of this research we discovered that simple vinylcyclopropanes such as **54**, prepared from enones and ethyl 2-bromocrotonate, cleave with trimethylsilyl iodide (TMSI) at low temperatures to give E/Z allylic iodides **55**.



54 55 56

Treatment of these iodides (major isomer: E=80%) with $Et_4N^+OH^-$ in DMF/H_2O gave good yields of diquinanes **56**.[58] The potential of this new [2+3] annulation as well as its brevity prompted us to investigate the opening of cyclopropanes **24a** and **24b**. Unfortunately, the TMSI reaction provided, in both cases, excellent yields of the Z isomer **57**, unsuited for cyclization, although treatment of this substance with base afforded the original vinylcyclopropane.[58] Further use of this method of

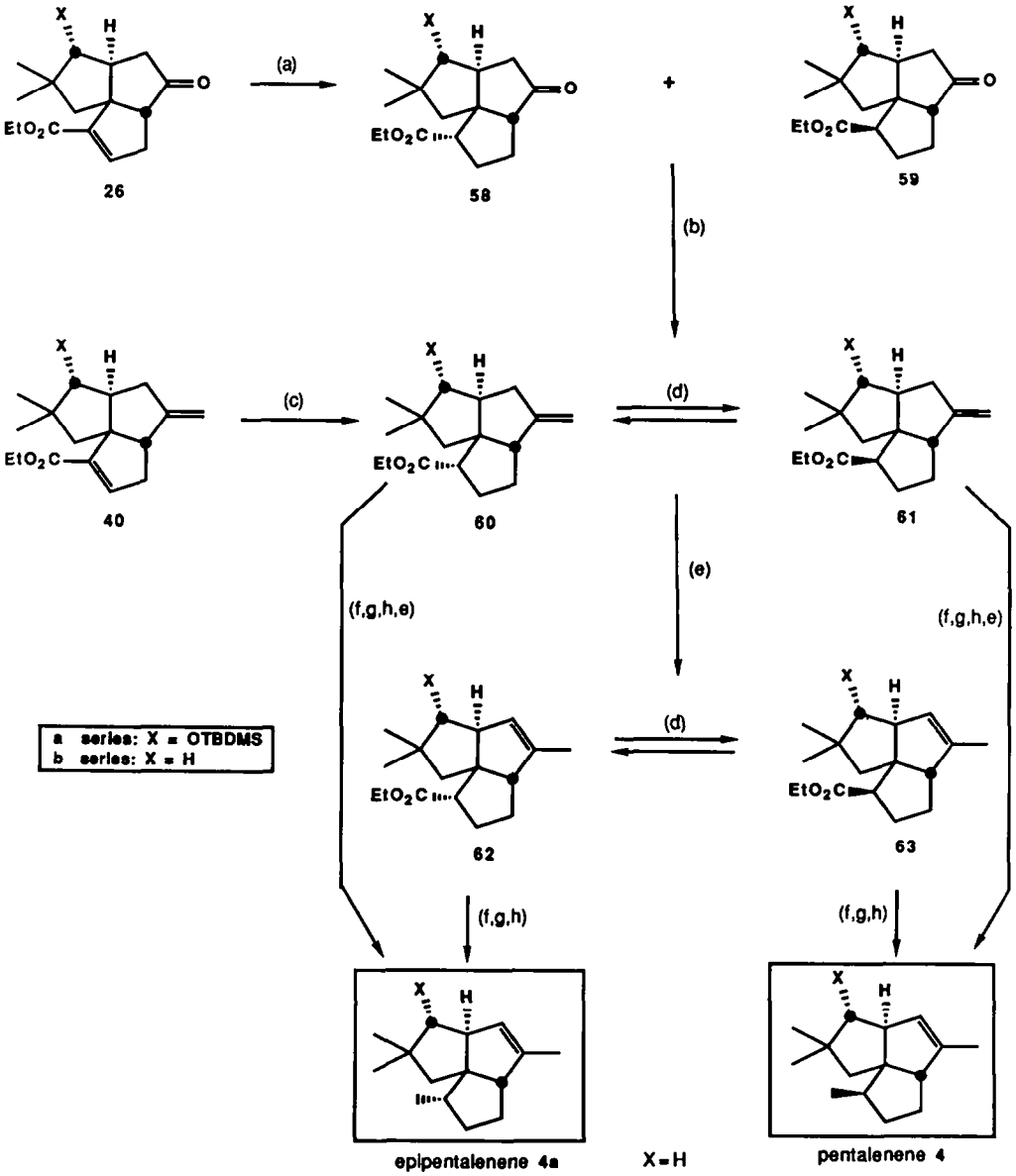


25 24 57

a series: X = OTBDMS
b series: X = H

cleavage awaits our investigating the various mechanisms operating on the nucleophilic opening of vinylcyclopropanes and optimizing the production of the required E isomer, whose presence does not depend on the original exo/endo ratios in the starting vinylcyclopropanes.[58,59]

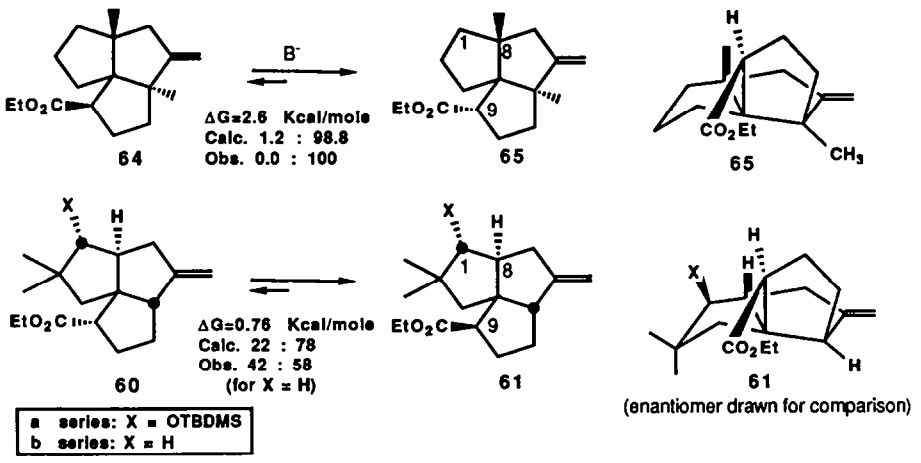
Final Transformations of Triquinanes. We now had two approaches to the title compounds: one stemming from keto esters **26**, obtained by ozonolysis of exocyclic olefins **40** and enol esters **45**, the other from olefinic esters **40**, Scheme 3. In the former case hydrogenation of **26a** and **26b** gave the saturated ketones **58** and **59** possessing predominantly the expected epi configuration of the ester functionality at C-9 with diastereomers **59** as minor products (pentalenic acid series **58a**:**59a**=80:20; pentalenene series: **58b**:**59b**=95:5). This was expected based on the approach of hydrogen from the less concave surface of the molecule.[60,61] Wittig reaction at room temperature afforded olefins **60** and **61**, Scheme 3.[62] In the latter case of olefinic esters **40**, an exciting result presented itself upon reduction of triquinanes **40** with Mg in MeOH.[63] The acrylate moiety was selectively saturated to provide selectively the olefins **60** and **61** (pentalenic acid series: **60a**:**61a**=9:1; pentalenene series: **60b**:**61b**=8:1), Scheme 3.[64] In this fashion the intermediate pool converged at the stage of ester-olefins **60** and **61**, which were obtained by several different routes.[65]



Reagents: a) H_2 / PtO_2, b)Ph_3PCH_3Br / Am^tOK / Am^tOH / PhH, c) Mg / MeOH, d) EtONa / EtOH / reflux, e) p-TsOH / CH_2Cl_2, f) $LiAlH_4$ / THF, g) MeCl / Et_3N / CH_2Cl_2, h) $LiEt_3BH$ / THF

Scheme 3

At this point we had greater than 9:1 control over C-9 stereochemistry in the epi series of the natural products. The issue of thermodynamic stability of anionic, radical, or cationic intermediates at C-9 was not settled in the literature.[66] Several reports advanced the notion that the natural configuration of the methyl group at C-9 should be more stable than the epi configuration.[67] We performed some calculations regarding the possible equilibrium between **60** and **61**, comparing these compounds to the conformations of our precursors to isocomenes, namely the triquinanes **64** and **65**.[68] The results of the calculations confirm the experimental facts in the isocomene series and suggest that the natural configuration of the ester in **65** is favored, Scheme 4.

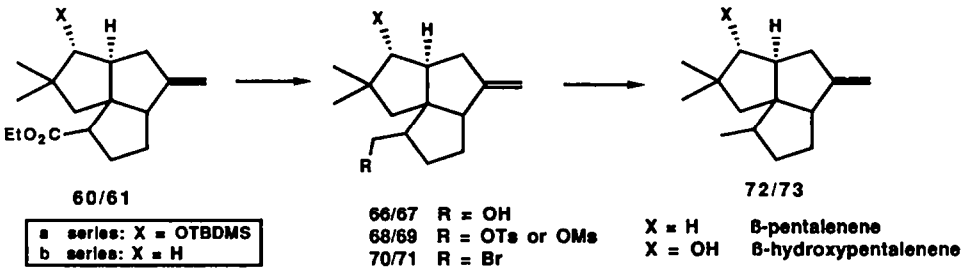


Scheme 4

On the other hand, calculations showed that the natural configuration should be favored only marginally in triquinanes **60** and **61**.[69] The possibility of equilibration of **60** and **61** did not present as clear cut case as that of the corresponding esters in the isocomene series, since the steric environment in the pentalenene nucleus is not as imposing as that in the angularly methylated triquinanes **64** and **65**.[70] Nevertheless, the base-catalyzed equilibration of **60** provided mixtures in which **61** predominated (70:30 in pentalenic acid series, 60:40 in pentalenene series). This observation can be understood more easily when stereo-drawings of isocomene ester **65** are compared with those of esters **61** drawn as their enantiomers for clarity, Scheme 4. When X=H, the interaction between the substituents of C-9 and C-1 is not as serious as when X=OTBDMS. In fact, should the substituent at C-1 be even bulkier than OTBDMS, chances are quite good that its van der Waal radius would force the ester to assume the position on the outer surface of the ring B/C diquinane, much as the methyl at C-8 in ester **65** had done. This means that the removal of a large substituent from C-8 can be compensated for by placing a slightly larger substituent at the adjacent carbon, C-1. This observation portends well for even greater selectivity in these isomerizations during any projected second-generation synthesis.

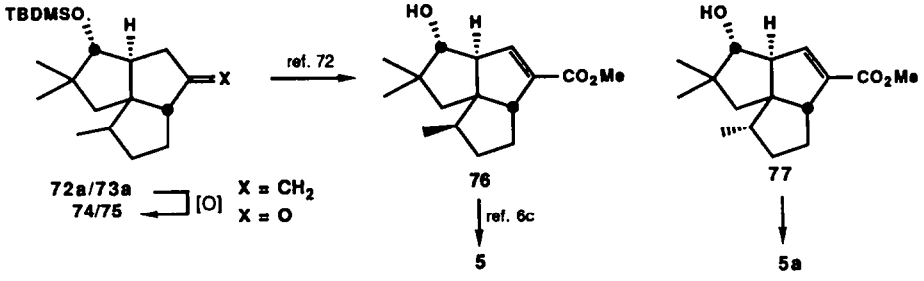
These esters had different R_f values on $AgNO_3$ impregnated silica and any separation and recycling should be done at this stage. Thus complete control could be obtained upon separation and a recycle of the epimer, although this task was found to be a complex one.[71] Because of the scarcity of material, in some of the series, the final transformations were frequently carried out on the mixtures at C-9 obtained from equilibrations, and the measure of stereoselectivity in these syntheses was evaluated at the stage of esters **60** and **61**, where separation is facile. The epimerization of endocyclic olefinic esters **62** and **63** was also studied and found less optimal than that of the exocyclic series, presumably because of the flattening of the diquinane nucleus comprised of ring B and C and a consequent reduction of steric hindrance.

The final functionalization to the natural products took place in analogy with the reductive operations in the isocomene series.[13j] Esters **60** and **61** were reduced to the alcohols **66** and **67** with $LiAlH_4$. These were converted to tosylates **68** and **69** and the tosylates exposed to $LiAlH_4$ again, Scheme 5. Because of the steric bulk of ring A, these tosylates were not displaced by hydride---rather they were "hydrolyzed" by the hydride attack on the sulfonyl groups. The tosylates were converted to bromides **70** and **71** and these were cleanly reduced with $LiAlH_4$ to β-pentalenenes **72b** and **73b** or β-hydroxypentalenene **72a** and **73a**. Isomerization of **72b** and **73b** gave a mixture consisting of epipentalenene and pentalenene. The ratios in these mixtures were either >9:1 (from compounds generated by reduction of **40b**) or 4:6 (from equilibrium mixtures).



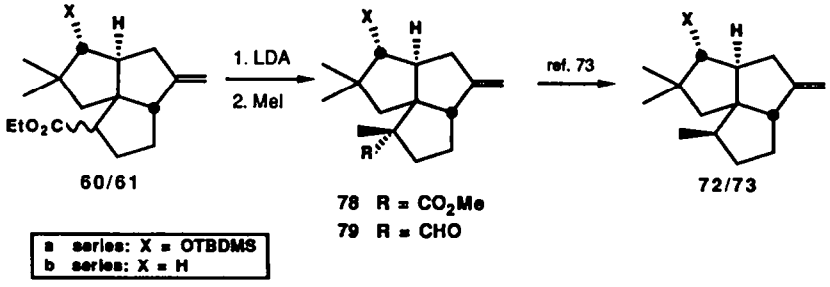
Scheme 5

The synthesis of pentalenic acids was completed by ozonolysis or periodate cleavage of **72** and **73** to provide ketones **74** and **75**. Conversion of this material to the enol triflate followed by Pd-catalyzed methoxycarboxylation[72] furnished, to our pleasant surprise, the deprotected alcohol as the t-butyldimethylsilyl group was cleaved during this operation to give directly pentalenic acid methyl ester **76** and its C-9 epimer **77** (1:9 from Mg reductions, 2:1 from equilibrations), Scheme 6. Both pentalenene and pentalenic acid were identified by comparison with spectra of synthetic natural products provided to us kindly by L. A. Paquette and M. Crimmins.



Scheme 6

Alkylative/decarbonylation approach to control of stereochemistry. The stereoselectivity in the epi series was greater than 90% as a consequence of the reduction or hydrogenation of the acrylate. Since the approach of the proton (or hydrogen) takes place from the less hindered ("natural") face of ring C, it follows that an alkylating agent may follow the same course. Indeed, exposure of the ester enolate anion derived from either **60a** and **60b**, or **61a** and **61b**, or their mixtures, to methyl iodide gave clearly alkylated esters **78a** and **78b**, Scheme 7.

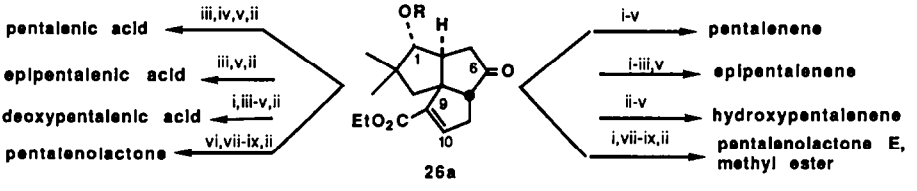


Scheme 7

The esters were transformed to aldehydes **79** by either DIBAL reduction or a combination sequence of $LiAlH_4$/PCC. Although a successful case of decarbonylation of a quaternary aldehyde exists,[73b] in our hands the use of Wilkinson's catalyst[73] under a variety of experimental conditions led to complex mixtures in which β-pentalenenes or β-hydroxy pentalenenes were present in trace amounts. Again, scarcity of material prevented us from improving on this procedure. However, the stereoselectivity of the alkylation has set the configuration at C-9, and it would remain to investigate a more effective method of stereoselective removal of the carboethoxy substitutent. In this light, the Wilkinson's conditions[73] or the Hunsdiecker reaction[74] would be investigated. In the latter case, a confirmation of equilibrium composition of stereoisomers derived via radical intermediates at C-9 would become available.[75]

Conclusion:

The stereoselective synthesis of pentalenic acid, pentalenene, epipentalenic acid, epi-pentalenene, and formally also deoxypentalenic acid and hydroxypentalenene have been carried out by a unified, system-oriented methodology involving the [4+1] intramolecular cyclopentene annulation. This strategy has proved extremely versatile in the construction of triquinane sesquiterpenes. Some new developments, such as the more efficient [2+3] annulation of enones, have surfaced during the course of this study. The preparation of all C-9 stereoisomers has provided us with valuable ^{13}C-NMR data of 1,2,3-trisubstituted cyclopentanes. This data becomes useful in elucidations of ring-function stereochemistry based on the ^{13}C-NMR shift of the secondary methyl substituents in these or any similar compounds[76]. Several approaches to stereocontrol at C-9 have been tested--the simplest one being the equilibration and separation of esters. The stereoselectivities were better than 9:1 in each series. Finally, these syntheses and the [2+3] annulation methodology may be combined in a second generation approach that will be asymmetric through the agency of chiral auxiliaries of 2-bromocrotonate esters. These investigations may finally provide the title compounds in optically pure form in less than ten steps from commercial materials. Finally, a word or two regarding the true potential of this methodology. Because the design addresses the functionalization of each ring it will be possible to convert the tricyclic material **26** to all of the terpenes of pentalenane class through relatively simple manipulations. The increased bulk at C-1 will permit complete stereocontrol in equilibrations to natural series, while the reduction of acrylate will provide the epi configurations at C-9. These investigations will be addressed during the second generation synthesis.



List of Operations : (i) reductive cleavage of C-1 alkoxide ;(ii) functionalization at C-6 ; (iii) reduction of acrylate at C-9 ; (iv) epimerization at C-9 ; (v) reduction of ester ; (vi) solvolysis of C-1 group and methyl migration ; (vii) deconjugation of acrylate ; (viii) oxidative cleavage of C-10/C-11 olefin ;(ix) α- methylene lactone formation at ring-C.

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Experimental Section

All nonhydrolytic reactions were carried out in a nitrogen or argon atmosphere, using standard techniques for the exclusion of air and moisture. Glassware used for moisture-sensitive reactions was flame-dried with an internal inert gas sweep. THF, ether, DME and benzene were distilled from benzophenone ketyl, dichloromethane and toluene from calcium hydride.

Analytical TLC was performed on silica gel 60F-254 plates. Flash chromatography was performed on Kieselgel 60 (230-400 mesh) by EM reagents. Mass spectra were recorded on a DuPont 20-491 or a Varian MAT-112 instrument (low resolution) or on a double focusing DuPont 21-110C or VGT instruments (exact mass). Infrared spectra were recorded on neat samples (NaCl plates) on a Perkin-Elmer 257 spectrometer. Proton NMR spectra were obtained on Varian EM390 or Bruker WP-270 instruments. Proton chemical shifts are reported in parts per million (ppm) downfield from tetramethylsilane (TMS) as an internal reference (0.0 ppm). Carbon NMR spectra were recorded on Bruker WP-270, or NR-80 instruments. Carbon chemical shifts are reported in ppm relative to TMS and the spectra were calibrated either to TMS or to the center line of the $CDCl_3$ triplet (77.02 ppm) and the multiplicity is indicated by CH_3, CH_2, CH, C (INEPT experiments).

1-Hydroxymethyl-3-[(tert-butyldimethylsilyl)oxy]-4,4-dimethylcyclopentene (18a).

In a procedure identical to the preparation of **18b** aldehyde **13a** (13.1 g, 0.05 mol) was reduced with sodium borohydride (2.31 g, 0.06 mol) in ether (115 mL) and MeOH (10 mL) to obtain the alcohol **18a**: 11.50 g, yield 87%; R_f=0.40 (hexane/ethyl acetate, 3:1); **IR** (neat) 3350 cm^{-1}; ^{1}**H-NMR** ($CDCl_3$) δ -0.01 (s, 3H), 0.02 (s, 3H), 0.86 (s, 9H), 0.95 (s, 3H), 1.1 (s, 3H), 1.96 (d, 1H, J=14 Hz), 2.18 (d, 1H, J=14 Hz), 4.12 (d, 2H, J=1.3 Hz), 4.22 (s, 1H), 5.44 (s, 1H); ^{13}**C-NMR** ($CDCl_3$) δ -4.7 (CH_3), -4.4 (CH_3), 18.3 (C), 23.4 (CH_3), 26.0 (CH_3), 28.2 (CH_3), 42.8 (C), 46.2 (CH_2), 61.8 (CH_2), 84.7 (CH), 126.8 (CH), 145.7 (C); **Mass Spectrum** (70 eV, m/e (rel. int.)) 256 (2, M^+), 199 (35), 107 (48), 91 (12), 79 (12), 75 (100), 73 (29).

1-Hydroxymethyl-4,4-dimethylcyclopentene (18b).

LiBr (41.0 g, 0.472 mol) was dissolved in 75 mL of DME and brought to reflux. 5,5-Dimethyl-2,3-epoxycyclohexanol[18,21] (22.1 g, 0.155 mol) in 75 mL of DME was added to the refluxing solution over 30 min. The reaction mixture was refluxed an additional 40 min, then cooled, diluted with 150 mL of pentane and washed 3x with 50 mL of H_2O. The aqueous layer was extracted with pentane and the combined organic layer was washed with brine, dried over Na_2SO_4, filtered, and evaporated to give 19.3 g (98.4%) of crude 4,4-dimethylcyclopentene-1-carboxaldehyde[18,21] **(13b)**. The crude aldehyde was dissolved in 600 mL of Et_2O and 15 mL of MeOH. Sodium borohydride (15 g, 0.4 mol) was added slowly in portions and the reaction mixture was stirred for 24 h. 3N HCl (100 mL) was added dropwise slowly into the flask. The aqueous layer was extracted 2x with 500 mL of Et_2O. The combined organic layer was washed with brine, dried over Na_2SO_4, filtered, and evaporated to give 17.82 g (90.8%) of alcohol **18b**, pure enough by NMR (>90%) to be used in the next step. An analytical sample was prepared by purification of 503 mg of crude material on flash silica with 10% Et_2O in hexane to yield 355 mg (70.6%) of alcohol **18b**: R_f=0.19 (15% EtOAc, 85% hexane). **IR** (neat)

3300, 1658 cm^{-1}; **^{1}H-NMR** ($CDCl_3$) δ 1.08 (s, 6H) 2.04, (s, 1H), 2.14 (m, 4H), 4.12 (s, 2H), 5.48 (s, 1H); **^{13}C-NMR** ($CDCl_3$) δ 29.9 (CH_3), 38.6 (C), 47.6 (CH_2), 47.8 (CH_2), 62.3 (CH_2), 124.0 (CH), 142.9 (C); **Mass Spectrum** (70 eV, m/e (rel. int.)) 108 (M^+-H_2O)(20), 96(11), 84(12), 69 (100), 55(20).

Ethyl-2-[2-[(tert-butyldimethylsilyl)oxy]-3,3-dimethyl-5-methylenecyclopentanyl]acetate (19a).

In a procedure identical to the preparation of **19b**, alcohol **18a** (5 g, 0.02 mol), triethyl orthoacetate (65 mL) and propionic acid (1 mL) were heated to 190-200° for 4 h to give after work up the ester **19a**: 5.7 g, yield 89% (trans:cis, 86:14); R_f=0.71 (hexane/ethyl acetate, 19:1); **IR** (neat) 1740, 1660 cm^{-1}; **^{1}H-NMR** ($CDCl_3$) δ -0.01 (s, 3H), 0.02 (s, 3H), 0.86 (s, 3H), 0.90 (s, 9H), 0.96 (s, 3H), 1.2 (t, 3H, J=7 Hz), 2.0-2.7 (m, 5H), 3.58 (d, 1H, J=9 Hz, for trans isomer), 3.73 (d, 1H, J=6 Hz, for cis isomer), 4.1 (q, 2H, J=7 Hz), 4.75 (s, 1H), 4.8 (s, 1H); **^{13}C-NMR** ($CDCl_3$) δ -4.1 (CH_3), 14.1 (CH_3), 18.0 (C), 20.7 (CH_3), 25.8 (CH_3), 27.0 (CH_3), 35.9 (CH_2), 39.9 (C), 45.8 (CH_2), 46.2 (CH), 60.0 (CH_2), 83.7 (CH), 106.7 (CH_2), 150.0 (C), 172.6 (C); **Mass Spectrum** (70 eV, m/e (rel. int.) 327 (0.2, M+1), 269 (84), 223 (34), 121, (81), 107 (23), 75 (100), 73 (53).
Anal. Calcd $C_{18}H_{34}O_3Si$: C, 66.26; H, 10.42. **Found:** C, 68.47; H, 10.62.

Ethyl-2-[4,4-dimethyl-2-methylenecyclopentanyl]acetate (19b).

Alcohol **18b** (0.240 g, 1.9 mmol) was dissolved in 15 mL of triethylorthoacetate and 0.5 mL of propionic acid was added. The mixture was then sealed in a glass tube and heated at approximately 200°C for 3 h. The tube was then cooled with liquid N_2 and the seal was broken. The mixture was dissolved in 50 mL of Et_2O, washed 3x with 10 mL of 1N HCl, 3x with 10 mL H_2O, and 2x with 10 mL of brine, dried over Na_2SO_4, filtered, and evaporatd to yield 0.285 g (76.3%) of crude oil. Filtration through a plug of silica gel yielded 0.279 g (74.7%) of product which was >90% pure by NMR and suitable for use in the next step. An analytical sample was then purified on 10% deactivated flash silica gel (to prevent olefin isomerization) with 5% EtOAc in hexane to yield pure olefinic ester **19b**. The reaction has been run on scales of up to 20 g of alcohol in a steel autoclave with similar results. R_f=0.63 (15% ethyl acetate, 85% hexane); **IR** (neat) 1738, 1655 cm^{-1}; **^{1}H-NMR** ($CDCl_3$) δ 0.96 (s, 3H), 1.05 (s, 3H), 1.19-1.28 (m, 1H), 1.26 (t, 3H, J=7.2 Hz), 1.79 (ddd, 1H, J_1=12.4, J_2=8.0, J_3=1.0 Hz), 2.02-2.23 (m, 2H), 2.26 (dd, 1H, J_1=15.2, J_2=9.3 Hz), 2.61 (dd, 1H, J_1=15.3, J_2=5.3 Hz), 2.94-3.02 (m, 1H), 4.13 (q, 2H, J=7.2 Hz), 4.78 (br.q, 1H, J=2.1 Hz), 4.89 (br.q, 1H, J=2.1 Hz); **^{13}C-NMR** ($CDCl_3$) δ 14.16 (CH_3), 27.56 (CH_3), 29.08 (CH_3), 37.14 (C), 38.97 (CH), 40.06 (CH_2), 47.34 (CH_2), 48.40 (CH_2), 60.15 (CH_2), 105.74 (CH_2), 155.32 (C), 173.06 (C); **Mass Spectrum** (70 eV, m/e (rel. int.)) 196 (20, M^+), 181 (20), 165 (25), 153 (100), 149 (35), 121 (55), 107 (60) 93 (60), 79 (40), 67 (50), 55 (85).
Calcd for $C_{12}H_{20}O_2$: 196.1198. **Found:** 196.1182.

2β-Carbethoxymethyl-3α-[tert-butyldimethylsilyl)oxy]-4,4-dimethylcyclopentanone (20a).

In a procedure identical to the preparation of **20b**, olefin **19a** (12 g, 0.037 mol) in 60 ml of CH_2Cl_2 was ozonized to obtain the ketone **20a**: 10 g, yield 83%; R_f=0.42 (hexane/ethyl acetate, 3:1); **IR** (neat) 1750, 1738 cm^{-1}; **^{1}H-NMR** ($CDCl_3$) δ -0.01 (s, 3H), 0.02 (s, 3H), 0.86 (s, 9H), 0.94 (s,

3H), 1.12 (s, 3H), 1.22 (t, 3H, J=7 Hz), 2.0-2.85 (m, 5H), 3.96 (d, 1H, J=10 Hz), 4.16 (q, 2H, J=7 Hz); **^{13}C-NMR** ($CDCl_3$) δ -4.0 (CH_3) (double intensity), 14.4 (CH_3), 18.4 (C), 21.5 (CH_3), 26.1 (CH_3), 27.5 (CH_3), 31.5 (CH_2), 38.9 (C), 51.7 (CH), 52.7 (CH_2), 60.9 (CH_2), 80.4 (CH), 172.0 (C), 215.0 (C); **Mass Spectrum** (70 eV, m/e (rel. int.)) 327 (M-1, .1), 271 (26), 151 (41), 127 (21), 123 (36) 95 (20), 75 (100).

Calcd for $C_{17}H_{32}O_4Si$: C, 62.20; H, 9.74. **Found:** C, 62.02; H, 9.77.

2-Carbethoxymethyl-4,4-dimethylcyclopentanone (20b)

Olefinic ester **19b** (2.48 g, 12.5 mmol)was dissolved in 100 mL of CH_2Cl_2 and 50 mL of MeOH, and O_2 was passed through the solution for 5 min and the mixture cooled to -78°C. Ozone was then bubbled through until the solution turned blue (~3 min) and then for 10 min more. The flow of ozone was replaced with O_2, which was bubbled through the solution until it became clear (~2 min) and then for 10 min more. The solution was transferred to a 250 mL round bottom flask and warmed to 0°C with stirring. Dimethyl sulfide (2 mL) was dropped into the flask and the solution was stirred for 24 h. The CH_2Cl_2 and DMS were removed by rotary evaporation. The crude oil was then dissolved in 20 mL of Et_2O, washed 4x with 5 mL of H_2O, 3x with 5 mL of brine, dried over Na_2SO_4, and evaporated to yield 2.41 g (96.4%) of crude material. This material was suitable for use in the next step. The material was purified on flash silica using 5→10% Et_2O in hexane and then distilled (Kugelrohr; 70°C/0.05 mm) to yield 934 mg (37.4%) of analytically pure ketoester **20b**. The yield was low because of to extensive polymerization. R_f=0.47 (20% EtOAc; 80% hexane); **IR** (neat) 1745, 1735, 1180, 1030 cm^{-1}; **^{1}H-NMR** ($CDCl_3$) δ 1.17 (s, 3H), 1.28 (s, 3H), 1.33 (t, 3H, J=7 Hz), 2.68 (t, 1H, J=12 Hz), 2.13 (dd, 1H, J_1=12, J_2=8 Hz), 2.22 (s, 2H), 2.52 (dd, 1H, J_1=16, J_2=8 Hz), 2.76 (m, 2H), 4.20 (q, 2H, J=7 Hz); **^{13}C-NMR** ($CDCl_3$) δ 13.9 (CH_3), 27.8 (CH_3), 29.5 (CH_3), 33.7 (C), 34.5 (CH_2), 43.3 (CH_2), 44.4 (CH), 52.4 (CH_2), 60.1 (CH_2), 171.5 (C), 217.7 (C); **Mass Spectrum** (70 eV, m/e (rel. int.)) 198 (M^+) (33), 183 (19), 153 (77), 152 (100), 149 (41), 137 (49), 111 (77), 83 (100), 56 (70), 55 (68);

Calcd for $C_{11}H_{18}O_3$: C, 66.67; H, 9.15. **Found:** C, 66.39; H, 9.28.

Ethyl 2α-[3-oxo-6α-[(tert-butyldimethylsilyl)oxy]-7,7-dimethyl-2-oxabicyclo[3.3.0]oct-1-yl]-3-butenoate (21a).

As in the procedure for the preparation of **21b**, the lactone **21a** was obtained in 83% yield as an inseparable mixture of erythro and threo isomers in a ratio of 3:1 as indicated by nmr data. The following assignments were made for the major isomer **21a**: R_f=0.40 (hexane/ethyl acetate, 9:1); **IR** (neat) 1780, 1732 cm^{-1}; **^{1}H-NMR** ($CDCl_3$) δ -0.01 (s, 3H), 0.02 (s, 3H), 0.86 (s, 9H), 0.92 (s, 3H), 0.98 (s, 3H), 1.21 (t, 3H, J=7 Hz), 1.7-2.8 (m, 6H), 3.43 (d, 1H, J=8 Hz), 4.18 (q, 2H, J=7 Hz), 5.25 (m, 2H), 5.92 (m, 1H): **^{13}C-NMR** ($CDCl_3$) δ -4.7 (CH_3), -4.3 (CH_3), 13.8 (CH_3), 17.8 (C), 22.3 (CH_3), 25.5 (CH_3), 26.9 (CH_3), 35.6 (CH_2), 42.0 (C), 47.6 (CH_2), 49.3 (CH), 59.1 (CH), 61.0 (CH_2), 86.3 (CH), 92.3 (C), 121.1 (CH_2), 131.3 (CH), 170.5 (C), 176.1 (C); **Mass Spectrum** (70 eV, m/e (rel. int.)) 396 (M^+, 0.4), 339 (19), 294 (16), 293 (70) 225 (25), 147 (17), 145 (29), 75 (100), 73 (43).

Ethyl 2α-(3-oxo-7,7-dimethyl-2-oxabicyclo[3.3.0]oct-1-yl)-3-butenoate (21b).

Dry zinc (1.5 g, 22.9 mmol) was covered with 4.5 mL of a saturated solution of $Cu(OAc)_2$ in acetic acid and allowed to stir for 30 min. The suspension was then washed 15x with 20 mL of Et_2O using an aspirator wand in order to remove the acetic acid. ^{1}H-NMR of the final Et_2O wash showed no acetic acid peak. The catalyst was then covered with 15 mL of dry ether and brought to reflux. A crystal of I_2 was added. A mixture of keto ester **20b** (0.5 g, 2.5 mmol) and ethyl 4-bromocrotonate (0.42 mL, 27.5 mmol) was added dropwise slowly over 10 min. No initiation was noticed after 10 min, so another crystal of I_2 was added causing rapid initiation. TLC showed the reaction to be complete after 4 h, whereupon it was quenched with 20 mL of saturated NH_4Cl. The aqueous layer was then extracted 3x with 10 mL of Et_2O; the organic layers were combined, washed with brine, dried over Na_2SO_4, and evaporated to yield 0.695 g (88.1% including 0.2 equiv of bromocrotonate) of crude oil. The material was then separated on flash silica using 15% EtOAc in hexane to yield 0.577 g (85.8%) of pure lactone **21b**. It was then purified by kugelrohr distillation at 150°C and 0.025 mm. to yield 0.449 g (66.8%) of analytically pure lactone **21b**. R_f = 0.33 (20% ethyl acetate, 80% hexane). The lactone was obtained as a mixture of erythro and threo isomers in a ratio of 7:3. **Major isomer (21b-erythro):** IR (neat) 1775, 1772, 1635 cm^{-1}; ^{1}H-NMR ($CDCl_3$) δ 0.98 (s, 3H), 1.18 (s, 3H), 1.27 (t, 3H, J=7 Hz), 1.44 (m, 1H), 1.91 (m, 3H), 2.35 (d, 1H, J=18 Hz), 2.76 (m, 1H), 2.98 (m, 1H), 3.24 (d, 1H, J=10 Hz), 4.15 (q, 2H, J=6 Hz), 5.31 (m, 2H), 5.91 (m, 1H); ^{13}C-NMR ($CDCl_3$) δ 13.9 (CH_3), 29.0 (CH_3), 29.7 (CH_3 double intensity), 36.8 (CH_2), 38.8 (C), 41.1 (CH), 48.1 (CH_2), 50.2 (CH_2), 58.5 (CH), 61.0 (CH_2), 97.2 (C), 121.0 (CH_2), 131.5 (CH), 170.6 (C), 176.5 (C).

Minor isomer (21b-threo): Not isolated in pure form. Peaks were assigned from spectra of threo and erythro mixtures: IR (neat) 1775, 1722, 1635 cm^{-1}; ^{1}H-NMR ($CDCl_3$) δ 1.02 (s, 3H), 1.18 (s, 3H), 1.27 (t, 3H, J=7 Hz), 1.44 (m, 1H), 1.91 (m, 3H), 2.35 (d, 1H, J=18 Hz), 2.76 (m, 1H), 2.98 (m, 1H), 3.36 (d, 1H, J=10 Hz), 4.15 (q, 2H, J=7 Hz), 5.31 (m, 2H), 5.91 (m, 1H); ^{13}C-NMR ($CDCl_3$) 13.9 (CH_3), 28.8 (CH_3), 29.7 (CH_3), 37.4 (CH_2), 38.6 (C), 40.8 (CH), 48.5 (CH_2), 49.9 (CH_2), 58.2 (CH), 61.0 (CH_2), 97.5 (C), 121.3 (CH_2), 131.1 (CH), 170.6 (C), 176.8 (C); **Mass Spectrum** (70 eV, m/e (rel. int.)) 223 (2)(M^++1-CO_2), 205(3), 153 (100), 135(14), 109(13), 83(14), 69(22), 55(18). **Calcd for** $C_{11}H_{18}O_3$ (diastereomeric mixture): C, 67.64; H, 8.32. **Found:** C, 67.56; H, 8.29.

[2α-[(tert-butyldimethylsilyl)oxy]-3,3-dimethyl-5-vinylcarbethoxymethylenecyclopent-1β-yl]acetic acid (22a).

Lactone **21a** (mixture of diastereomers, 3.5 g, 8.83 mmol) was dissolved in 22 mL of DME and cooled to 0°C. 1,8-Diazabicyclo[5.4.0]undec-7-ene (DBU) (1.47 mL, 9.7 mmol) in 10 mL of DME was added dropwise over a 5 min period. The cooling bath was removed, and the dark reddish-brown mixture was stirred at ambient temperature for 12 h. Ice-cold 1N HCl (ca. 50 mL) was added, followed by 100 mL of CH_2Cl_2, and the light yellow mixture was stirred for 10 min. The organic layer was separated, and the aqueous layer was extracted with CH_2Cl_2 (2x25 mL). The combined extracts were washed with brine, dried over $MgSO_4$ and the solvent evaporated to give 3.2 g of crude

material, which was chromatographed (silica gel, hexane/ethyl ether, 2:1) to give 2.8g (80%) of a mixture of acids (3:2, Z:E). For analytical samples, this mixture was rechromatographed (silica, 10-30% ethyl acetate in hexanes containing 1% acetic acid) to furnish pure diastereomers.

22a (Z, major diastereomer): R_f=0.30 (hexane/ethyl ether, 1:1); **IR** (neat) 3500-3100, 1715 cm^{-1}; **^{1}H-NMR** ($CDCl_3$) δ -0.01 (s, 3H), 0.02 (s, 3H), 0.81 (s, 3H), 0.86 (s, 9H), 1.03 (s, 3H), 1.3 (t, 3H, J=7 Hz), 2.2-3.10 (m, 6H), 3.89 (d, 1H, J=8 Hz), 4.24 (q, 2H, J=7 Hz) 5.20 (m, 2H), 6.4 (m, 1H); **^{13}C-NMR** ($CDCl_3$) δ -4.3 (CH_3), -4.27 (CH_3), 13.9 (CH_3), 18 (C), 20.7 (CH_3), 25.7 (CH_3), 26.6 (CH_3), 35.0 (CH_2), 40.7 (C), 45.6 (CH_2), 46.6 (CH), 60.5 (CH_2), 83.7 (CH), 116.4 (CH_2), 126.5 (C), 131.9 (CH), 152.9 (C), 167.8 (C), 177.0 (C), **Mass Spectrum** (70 eV, m/e (rel. int.)) 397 (M+1, 0.1), 340 (22), 339 (83), 293 (56), 265 (30), 225 (22), 151 (47), 75 (100), 73 (77).

Anal. Calcd $C_{21}H_{36}O_5Si$: C, 63.64; H, 9.05. **Found:** C, 63.66; H, 9.29.

22a (E, minor diastereomer): R_f=0.38 (hexane/ethyl ether, 1:1); **^{1}H-NMR** ($CDCl_3$) δ -0.01 (s, 3H), 0.02 (s, 3H), 0.84 (s, 3H), 0.88 (s, 9H), 0.92 (s, 3H), 1.31 (t, 3H, J=7 Hz), 2.19 (d, 1H, J=14 Hz), 2.2 (dd, 1H, J_1=14, J_2=5 Hz), 2.55 (d, 1H, J=14 Hz), 3.10 (dd, 1H, J_1=14, J_2=8 Hz), 3.56 (m, 1H), 3.83 (d, 1H J=8 Hz), 4.25 (q, 2H, J=7 Hz), 5.18 (d, 1H, J=11 Hz), 5.25 (d, 1H, J=17 Hz), 6.39 (dd, 1H, J_1=17, J_2=11 Hz); **^{13}C-NMR** ($CDCl_3$) δ -4.9 (CH_3), -4.5 (CH_3), 14.1 (CH_3), 18.0 (C), 22.6 (CH_3), 25.7 (CH_3), 27.5 (CH_3), 33.5 (CH_2), 41.2 (C), 41.8 (CH_2), 44.5 (CH), 60.4 (CH_2), 79.3 (CH), 116.3 (CH), 128 (C), 130.5 (CH), 151.5 (C), 168.0 (C), 178.4 (C).

(3,3-Dimethyl-5-vinylcarbethoxymethylenecyclopent-1β-yl)acetic acid (22b).

A solution of DBU (5.72 g, 37.6 mmol) in 100 mL of DME was added dropwise to a stirred solution of lactone **21b** (5.01 g, 18.8 mmol) in 100 mL of DME over 1 h. The solution was stirred for an additional 1 h at which time the volume of the mixture was reduced to approximately 50 mL by evaporation and partitioned between 100 mL of 3N HCl and 100 mL of CH_2Cl_2. The layers were separated and the aqueous layer was washed 2x with 50 mL of CH_2Cl_2. The combined organic layers were extracted 5x with a solution of 20% K_2CO_3 in 5% aqueous KOH. The organic layer was dried over Na_2SO_4, filtered, and evaporated to give 0.88 g (17.6%) of recovered **21b**. The basic layer was acidified to pH=1 with 3N HCl and extracted 3x with CH_2Cl_2. The organic layer was dried over Na_2SO_4, filtered and evaporated to give 3.3 g (65.1%; 79% based on recovered starting material) of dienic acid **22b** as an inseparable 2:1 mixture of E and Z isomers which was clean enough to be used in the next step. For analytical purposes, a portion of **22b** was purified on flash silica (10% to 30% EtOAc in hexane containing 2% AcOH). R_f=0.22 (20% EtOAc and 2% HOAc in hexane); **IR** (neat) 3100 v.br., 1715, 1640 cm^{-1}; **Mass Spectrum** (70 eV, m/e (rel. int.)) 266 (M^+, 8), 251 (2), 238 (4), 223 (10), 205 (6), 193 (25), 149 (100), 141 (15), 127 (10), 114 (12), 83 (15), 69 (20).

Calcd for $C_{15}H_{22}O_4$: 266.1518. **Found:** 266.1515.

22b (E, major isomer): **^{1}H-NMR** ($CDCl_3$) δ 0.86 (s, 3H), 1.12 (s, 3H), 1.30-1.43 (m, 4H), 1.81-2.03 (m, 1H), 2.27-2.49 (m, 3H), 2.82 (dd, 1H, J_1=15.5, J_2=3.2 Hz), 3.26-3.40 (m, 1H), 4.27 (q, 2H, J=7.2 Hz), 5.18-5.42 (m, 2H), 6.42 (dd, J_1=17.1, 1H, J_2=11.3 Hz); **^{13}C-NMR** ($CDCl_3$) δ 14.03 (CH_3), 27.39 (CH_3), 28.78 (CH_3), 37.58 (C), 37.90 (CH), 40.09 (CH_2), 46.69 (CH_2), 47.94 (CH_2), 60.64 (CH_2), 116.39 (CH_2), 127.32 (C), 132.44 (CH), 154.40 (C), 167.60 (C), 178.23 (C).

22b (Z, minor isomer): ^{1}H-NMR ($CDCl_3$) δ 0.86 (s, 3H), 1.12 (s, 3H), 1.30-1.43 (m, 4H), 1.81-2.03 (m, 1H), 2.27-2.49 (m, 3H), 2.75 (dd, 1H, J_1=15.5, J_2=3.2 Hz), 3.47-3.61 (m, 1H), 4.26 (q, 2H, J=7.2 Hz), 5.18-5.42 (m, 2H), 6.44 (dd, 1H, J_1=17.2, J_2=11.5 Hz); ^{13}C-NMR ($CDCl_3$) δ 14.18 (CH_3), 27.16 (CH_3), 28.56 (CH_3), 38.36 (C), 37.90 (CH), 40.16 (CH_2), 47.16 (CH_2), 47.94 (CH_2), 60.51 (CH_2), 116.62 (CH_2), 126.96 (C), 130.14 (CH), 156.12 (C), 167.38 (C), 177.98 (C).

(1α,6α)-8,8-Dimethyl-7α-[(tert-butyldimethylsilyl)oxy]-2β-carbethoxy-2α-vinyltricylo[4.3.0.0^{1,3}] nonan-4-one (24a) and Its 2α,2β isomer.

Dienic acids **22a** (1.9 g, 3.8 mmol) were dissolved in 30 mL of dry benzene. Freshly distilled oxalyl chloride (0.85 mL, 9.6 mmol) was added in one portion, and the mixture was stirred at room temperature for 2.5 h. Completion of reaction was ascertained by concentrating an aliquot in vacuo and examining it IR spectrum. Acid chloride: IR (neat) 1800, 1715 cm^{-1}.

Ethereal diazomethane was prepared by the slow addition (at 0°C) of N-nitrosomethylurea (4.94 g, 48 mmol) to a two-phase system consisting of 90 mL of 50% aqueous potassium hydroxide and 100 mL of ether kept at 0°C. The solution was swirled as addition proceeded, and after 15 min the ethereal layer was decanted into a precooled flask, and 1 mL of dry triethylamine was added.

To this mixture was added dropwise with cooling and stirring the acid chloride in 15 mL of anhydrous ether. The resulting cloudy suspension was stirred an additional 0.5 h at 0°C and filtered with suction through a medium frit. The clear filtrate was concentrated in vacuo, diluted with 3:1 hexane/Et_2O and filtered through basic alumina, eluting with the same solvent. Concentration of the eluent in vacuo gave 1.8g (90%) of mixed diazo ketones **23a**: IR (neat) 2080, 1710 cm^{-1}.

A solution of diazo ketones **23a** (1.8 g, 4.3 mmol) in 22 mL of dry benzene was added over a 10-min period to 180 mL of refluxing benzene containing 7.2 g of anhydrous cupric sulfate and 0.2 g of cupric acetylacetonate. The mixture was kept at reflux for 1.5 h, cooled to room temperature and filtered through celite. The filtrate was concentrated in vacuo and dissolved in anhydrous ethyl ether and the resulting suspension was filtered through a plug of basic alumina. This filtrate was concentrated in vacuo to give 1.2 g of crude vinylcyclopropanes. The mixture was chromatographed (silica, hexane/ethyl acetate, 9:1) to give 0.28 g of **24a-endo**, 0.43 g of **24a-exo**, and 0.03 g of mixture (45% based on dienic acids **22a**).

24a-endo (minor diastereomer): R_f=0.55 (hexane/ethyl acetate, 9:1); ^{1}H-NMR ($CDCl_3$) δ -0.01 (s, 3H), 0.02 (s, 3H), 0.83 (s, 9H), 0.91 (s, 3H), 0.96 (s, 3H), 1.24 (t, 3H, J=7 Hz), 1.62 (d, 1H, J=14 Hz), 1.73 (d, 1H, J=14 Hz), 2.15 (m, 2H), 2.41 (m, 1H), 2.62 (s, 1H), 3.56 (d, 1H, J=8 Hz), 4.16 (q, 2H, J=7 Hz), 5.2 (d, 1H, J=17 Hz), 5.31 (d, 1H, J=10 Hz), 5.9-6.09 (dd, 1H, J_1=17, J_2=10 Hz); ^{13}C-NMR ($CDCl_3$) δ -4.4 (CH_3), -3.9 (CH_3), 14.1 (CH_3), 18.0 (C), 21.5 (CH_3), 26.7 (CH_3), 40.0 (C), 40.3 (CH_2), 42.2 (C), 43.4 (CH_2), 44.4 (CH), 45.3 (CH_2), 47.5 (C), 61.3 (CH_2), 86.4 (CH) 121.4 (CH_2), 130.0 (CH), 168.9 (C), 212.6 (C).

24a-exo (major diastereomer): R_f=0.38 (hexane/ethyl acetate, 9:1); IR (neat) 1745, 1720, 1250, 830 cm^{-1}; ^{1}H-NMR ($CDCl_3$) δ -0.01 (s, 3H), 0.02 (s, 3H), 0.84 (s, 9H), 0.93 (s, 3H), 0.98 (s, 3H), 1.24 (t, 3H, J=7 Hz), 1.45 (d, 1H, J=14 Hz), 1.79 (d, 1H, J=14 Hz), 2.09 (s, 1H), 2.1-2.48 (m,

3H), 3.49 (d, 1H, J=8 Hz), 4.17 (q, 2H, J=7 Hz), 5.0 (d, 1H, J=17.5 Hz), 5.16 (d, 1H, J=11 Hz), 5.8-5.9 (dd, 1H, J_1=17.5, J_2=11 Hz); **^{13}C-NMR** ($CDCl_3$) δ -4.4 (CH_3), -3.9 (CH_3), 14.1 (CH_3), 18.1 (C), 21.4 (CH_3), 25.7 (CH_3), 26.7, (CH_3) 39.0 (CH_2), 42.8 (C), 44.6 (CH), 44.7 (CH_2), 45.6 (C), 46.1 (CH), 48.8 (C), 61.6 (CH_2), 87.2 (CH), 116.6 (CH_2), 132.7 (CH), 168.2 (C), 211.6 (C); **Mass Spectrum** (70 eV, m/e (rel. int.)) 393 (M +1, 29), 232 (44), 214 (98), 187 (60), 159 (80), 145 (45), 129 (59), 73 (100).

Calcd for $C_{22}H_{36}O_4Si$: 392.2382. **Found:** 392.2380.

(1α,6α)-8,8-Dimethyl-2β-carbethoxy-2α-vinyltricyclo[4.3.0.0^{1,3}]nonan-4-one (24b) and its 2α, 2β isomer.

a, By cyclopropanation of diazo ketone **23b**:

Dienic acid **22b** (521 mg, 1.96 mmol) was dissolved in 20 mL of dry benzene and cooled to 5°C. Oxalyl chloride (427 μL, 4.90 mmol) was then added, and the solution was allowed to warm to room temperature. The reaction was monitored by IR which showed complete conversion to acid chloride after 2 h. The solution was then freeze-dried. **IR** (neat) 1795, 1720 cm^{-1}.

Diazomethane was prepared by addition of nitrosomethylurea (2.00g, 19.4 mmol) to a two-phase system consisting of 25 mL of Et_2O and 25 mL of 50% KOH at 0°C. The ether layer was dried for 30 min over KOH pellets, then over Na_2SO_4 for 5 min at 0°C in both cases. Triethylamine (1 mL) was added to the solution which was subsequently filtered through a cotton plug into the round bottom flask which contained the dry acid chloride. The solution was allowed to stir for 45 min at 0°C. IR at this time showed complete coversion to diazoketone **23b**. The solution was then gently refluxed for 10 min with a heat gun to remove excess CH_2N_2, filtered through a medium frit and freeze-dried. **IR** (neat) 2100, 1720, 1635 cm^{-1}.

Cupric sulfate (300 mg, 1.88 mmol) and cupric acetylacetonate (30 mg, 0.115 mmol) were suspended in 15 mL of dry benzene and brought to reflux. The crude diazo ketone was dissolved in 10 mL of dry benzene and added dropwise over 15 min. to the refluxing suspension. The mixture was refluxed for an additional 40 min, at which time it was cooled to room temperature, evaporated to dryness, and diluted with 20 mL of hexane. This mixture was filtered through celite and evaporated to give 498 mg of crude oil shown by NMR analysis to be a 2:1 mixture of **24b-endo** and **24b-exo**. The crude mixture was separated on flash silica gel using 0→25% EtOAc in hexane as eluant to give a less polar (174 mg, 34%) (**24b-endo**) and a more polar (148 mg, 29%) (**24b-exo**) diastereomer of the desired vinylcyclopropane.

24b-endo (minor diastereomer): R_f=0.33 (Hexane 85%, EtOAc 15%); b.p. 80°/10^{-4}mm Hg (Kugelrohr temp.); **IR** (neat) 1735, 1640 cm^{-1}; **^{1}H-NMR** ($CDCl_3$) δ, 1.06 (s, 3H), 1.12 (s, 3H), 1.26 (t, 3H, J=7.0 Hz), 1.39 (dd, 1H, J_1=12.5, J_2=10.5 Hz), 1.66 (dd, 1H, J_1=14.0, J_2=1.5 Hz), 1.82 (d, 1H, J=14.0 Hz), 1.93 (ddd, 1H, J_1=13.0, J_2=7.5, J_3=1.5 Hz), 2.00 (m, 1H), 2.22 (ddd, 1H, J_1=20.0, J_2=8.0, J_3=1.0 Hz), 2.66 (m, 1H), 2.70 (s, 1H), 4.16 (m, 2H), 5.24 (dd, 1H, J_1=17.5, J_2=1.0 Hz), 5.34 (dd, 1H, J_1=10.0, J_2=1.0 Hz), 6.08 (dd, 1H, J_1=17.0, J_2=10.0 Hz); **^{13}C-NMR** ($CDCl_3$) δ 14.20 (CH_3), 28.76 (CH_3), 29.25 (CH_3), 37.81 (CH), 39.44 (C), 41.70 (C), 43.36 (CH_2), 44.73 (CH_2), 46.00 (CH), 49.22 (CH_2), 53.17 (C), 61.43 (CH_2), 121.44 (CH_2), 130.44 (CH), 169.53 (C), 213.49 (C); **Mass Spectrum** (70

eV, m/e (rel. int.)) 262 (M^+, 8), 216 (100), 201 (20), 173 (25), 161 (30), 146 (20), 131 (20), 125 (25), 119 (10), 105 (25), 97 (10), 91 (30), 77 (20).

Calcd for $C_{16}H_{22}O_3$: C, 73.25; H, 8.45. **Found:** C, 73.10; H, 8.45.

24b-exo (major diastereomer): R_f=0.24 (hexane 85%; EtOAc 15%); b.p. 80°/10^{-4}mm Hg (kugelrohr temp.); **IR** (neat) 1735, 1635 cm^{-1}; **^{1}H-NMR** ($CDCl_3$) δ 1.07 (s, 3H), 1.11 (s, 3H), 1.28 (t, 1H, J=14.0 Hz), 1.83 (dd, 1H, J_1=12.0, J_2=10.0 Hz), 1.54 (d, 1H, J=14.0 Hz), 1.83 (dd, 1H, J_1=14.0, J_2=1.0 Hz), 1.95 (ddd, 1H, J_1=12.5, J_2=7.5, J_3=1.5 Hz), 2.07 (dd, 1H, J_1=19.5, J_2=3.5 Hz), 2.16 (s, 1H), 2.41 (dd, 1H, J_1=19.0, J_2=8.0 Hz), 2.63 (m, 1H), 4.20 (m, 2H), 5.10 (d, 1H, J=17.5 Hz), 5.18 (d, 1H, J=10.5 Hz), 5.83 (dd, 1H, J_1=17.0, J_2=10.5 Hz); **^{13}C-NMR** ($CDCl_3$) δ, 14.06 (CH_3), 28.50 (CH_3), 29.11 (CH_3), 38.94 (CH_2), 39.79 (C), 42.46 (CH_2), 45.44 (CH_3), 49.68 (CH_3), 53.63 (C), 61.46 (CH_2), 116.22 (CH_2), 133.45 (CH), 169.02 (C), 212.11 (C); **Mass Spectrum** (70 eV, m/e (rel. int.)) 262 (M^+, 45), 247 (10), 234 (15), 216 (70), 205 (20), 188 (100), 173 (40), 161 (45), 151 (70), 145 (55), 140 (50), 132 (65), 123 (70), 105 (80), 91 (80), 77 (45).

Calcd for $C_{16}H_{22}O_3$: C, 73.25; H, 8.45. **Found:** C, 72.87; H, 8.80.

b, By cyclopropanation of enone **25:**

A solution of lithium diisopropylamide (prepared from 0.073 g (0.72 mmol) of diisopropylamine in 0.7 mL of THF and 0.29 mL of n-BuLi (2.5M in hexane) at 0°C) was cooled to -78°C and HMPA (0.14 mL, 0.72 mmol) was added. After 30 min ethyl 2-bromocrotonate (0.127 g, 0.66 mmol) was introduced via a syringe. The dark brown solution was warmed up to 0°C and was stirred for 10 min whereupon the enone **25** (0.1 g, 0.72 mmol) was added via a syringe. After 15 min the reaction was quenched at 0°C with saturated NH_4Cl solution, diluted with ether and washed with 3N HCl. The aqueous layers were combined, washed with brine, dried (Na_2SO_4), and evaporated to yield 0.17 g of crude product shown to consist of a 1:1 (45%) mixture of **24b-exo** and **24b-endo** vinylcyclopropanes.

(1α,6α)-8,8-Dimethyl-7α-hydroxy-2β-carbethoxy-2α-vinyltricyclo[4.3.0.$0^{1,3}$]nonan-4-one (24c) and Its 2α,2β Isomer.

To a stirred solution of the silyl ether **24a-endo** (0.23 g, 0.58 mmol) in 10 mL of THF was added a solution of tetra-n-butylammonium fluoride (1.76 mL of a 1 M solution) in THF. After 3 h, the solution was diluted with 50 mL of ether and washed with saturated aqueous $NaHCO_3$ (2 x 5 mL). The aqueous layer was extracted with ether (2 x 10 mL), the combined organic layers were washed with brine and dried over $MgSO_4$. Evaporation of the solvent yielded a yellow oil, which was chromatographed (silica, hexane/ethyl acetate 1:1) to obtain pure **24c-endo** as a pale yellow oil: 153 mg, 94%; R_f=0.31 (hexane/ethyl acetate, 1:1); **IR** (neat) 3450, 1730, 740 cm^{-1}; **^{1}H-NMR** ($CDCl_3$) δ 0.93 (s, 3H), 1.01 (s, 3H), 1.18 (t, 3H, J=7 Hz), 1.6-2.6 (m, 7H), 3.45 (d, 1H, J=9 Hz), 4.05 (m, 2H), 5.14 (d, 1H, J=17 Hz), 5.27 (d, 1H, J=10 Hz), 5.96 (dd, 1H, J_1=17, J_2=10 Hz); **^{13}C-NMR** ($CDCl_3$) δ 14.1 (CH_3), 21.5 (CH_3), 26.6 (CH_3), 39.0 (C), 40.7 (CH_2), 41.6 (C), 42.7 (CH_2), 43.9 (C), 45.6 (CH), 47.2 (CH), 61.5 (CH_2), 85.6 (CH), 121.6 (CH_2), 129.8 (CH), 169.0 (C), 212.8 (C); **Mass Spectrum** (70 eV, m/e (rel. int.)) 278 (2, M^+), 232 (10), 219 (4), 161 (20), 151 (15), 105 (20), 91 (25), 67 (100).

Calcd for $C_{16}H_{22}O_4$: 278.1518. **Found:** 278.1440.

The silyl ether **24a-exo** was converted to the alcohol **24c-exo** by a similar procedure.

24c-exo: R_f=0.21 (hexane/ethyl acetate, 1:1); **IR** (neat) 3400, 1750, 1720, 1190 cm^{-1}; ^{1}**H-NMR** ($CDCl_3$) δ 0.96 (s, 3H), 1.0 (s, 3H), 1.21 (t, 3H, J=7 Hz), 1.50 (d, 1H, J=14 Hz), 1.83 (d, 1H, J=14 Hz), 2.0 (s, 1H), 2.16 - 2.4 (m, 5H), 2.5 (bs, 1H), 3.48 (d, 1H, J=8 Hz), 4.13 (m, 2H), 5.0 (d, 1H, J=17 Hz), 5.15 (d, 1H, J=11 Hz), 5.8 (dd, 1H, J_1=17, J_2=11 Hz); ^{13}**C-NMR** ($CDCl_3$) δ 14.0 (CH_3), 21.0 (CH_3), 26.4 (CH_3), 39.4 (CH_2), 42.0 (C), 43.5 (CH_2), 44.7 (CH), 45.2 (CH) 45.4 (C), 47.9 (C), 61.6 (CH_2), 86.4 (CH), 116.7 (CH_2), 132.5 (CH), 168.7 (C), 211.6 (C).

(1α,6α)-8,8-Dimethyl-7α-hydroxy-2β-carbethoxy-2α-vinyl-4-methylenetricyclo[4.3.0.0^{1,3}]nonane (39c) and Its 2α, 2β Isomer.

Methyltriphenylphosphonium bromide (360 mg, 1 mmol) was suspended in 5 mL of dry benzene. A benzene solution of freshly prepared potassium tert-amylate (0.7 mL of a 1.5 M solultion) was added, and the resulting yellow suspension was stirred at room temperature for 30 min. Hydroxyketone **24c-endo** (140 mg, 0.5 mmol) in 2 mL of benzene was added dropwise over a period of 2 min. The yellow-brown reaction mixture was stirred at room temperature for 3 h, whereupon it was quenched with 5 mL of saturated NH_4Cl solution and extracted with ether (3 x 20 mL). The combined organic extracts were washed once with saturated NH_4Cl and dried over $MgSO_4$. Evaporation of solvents yielded a viscous mass which was chromatographed (silica, hexane/ethyl acetate, 3:1) to obtain pure **39c** as an oil: 112 mg, 81%; R_f=0.4 (hexane/ethyl acetate, 3:1); **IR** (neat) 3450, 1730, 740 cm^{-1}; ^{1}**H-NMR** ($CDCl_3$) δ 0.95 (s, 3H), 1.04 (s, 3H), 1.23 (t, 3H, J=7 Hz), 1.5-2.3 (m, 5H), 2.5 (s, 1H), 3.4 (d, 1H, J=9 Hz), 4.08 (q, 2H, J=7 Hz), 4.8 (s, 1H), 5.0 (s, 1H), 5.3 (m, 2H), 5.7 (m, 1H); ^{13}**C-NMR** ($CDCl_3$) δ 14.2 (CH_3), 22.0 (CH_3), 27.1 (CH_3), 36.1 (CH_2), 39.6 (C), 41.2 (CH_2), 41.7 (C), 45.1 (CH), 47.4 (C), 49.4 (CH), 60.9 (CH_2), 84.4 (CH), 108.7 (CH_2), 120.7 (CH_2), 130.8 (CH), 150.6 (C), 170.9 (C); **Mass Spectrum** (70 eV, m/e (rel. int.)) 276 (50, M^+), 243 (37), 230 (35), 203 (30), 185 (100), 131 (95), 117 (60), 91 (90).

Calcd for $C_{17}H_{24}O_3$: 276.1725 **Found**: 276.1723.

Similar procedure was followed to prepare **39c-exo**: ^{1}**H-NMR** ($CDCl_3$) δ 0.94 (s, 3H), 1.0 (s, 3H), 1.18 (t, 3H, J=7 Hz), 1.6-2.45 (m, 7H), 3.43 (d, 1H, J=8 Hz), 4.13 (m, 2H), 4.9 (s, 1H), 5.1 (s, 1H), 5.21 (m, 2H), 5.52 (m, 1H).

(1α,6α)-8,8-Dimethyl-7α-[(tert-butyldimethylsilyl)oxy]-2β-carbethoxy-2α-vinyl-4-methylenetricyclo-[4.3.0.0^{1,3}]nonane (39a) and Its 2α, 2β Isomer.

To a solution of the alcohol **39c-endo** (110 mg, 0.4 mmol) in 4 mL of dry DMF was added imidazole (54 mg, 0.8 mmol) followed by tert-butyldimethylsilyl chloride (121 mg, 0.8 mmol). The mixture was stirred at room temperature for 18 h, whereupon it was diluted with ether (30 mL) and poured into saturated NaCl solution (10 mL). The organic layer was separated and the aqueous layer extracted with ether (2 x 15 mL). The combined extracts were dried over $MgSO_4$ and the solvent evaporated to give the crude material which was chromatographed (silica, hexane/ethyl acetate, 19:1) to obtain pure **39a-endo** as a colorless oil: 130 mg, 83%; R_f=0.34 (hexane/ethyl acetate, 19:1); **IR** (neat) 1735, 1130, 790 cm^{-1}; ^{1}**H-NMR** ($CDCl_3$) δ 0.01 (s, 3H), 0.03 (s, 3H), 0.85 (s, 9H),

0.9 (s, 3H), 0.96 (s, 3H), 1.2 (t, 3H, J=7 Hz), 1.61 (d, 1H, J=14 Hz), 1.7 (d, 1H, J=14 Hz), 2.1-2.3 (m, 3H), 2.5 (s, 1H), 3.4 (d, 1H, J=8.5 Hz), 4.09 (q, 2H, J=7 Hz), 4.86 (s, 1H), 5.02 (s, 1H), 5.23-5.27 (dd, 1H, J_1=1.8, J_2=10.5 Hz), 5.24-5.31 (dd, 1H, J_1=17.5, J_2=1.8 Hz), 5.7-5.9 (dd, 1H, J_1=17.5 Hz, J_2=10.5 Hz); **^{13}C-NMR** ($CDCl_3$) δ -4.3 (CH_3), -3.86 (CH_3), 14.3 (CH_3), 18.1 (C), 22.5 (CH_3), 25.9 (CH_3), 27.4 (CH_3), 36.8 (CH_2), 39.8 (C), 41.0 (CH_2), 42.6 (C), 45.0 (CH), 48.0 (C), 50.0 (CH), 60.7 (CH_2), 85.2 (CH), 108.2 (CH_2), 120.5 (CH_2), 131.0 (CH), 151.1 (C), 170.9 (C); **Mass Spectrum** (70 eV, m/e (rel. int.)) 390 (6, M^+), 333 (32), 287 (6), 258 (6), 185 (60), 143 (25), 129 (32), 73 (100).

Calcd for $C_{23}H_{38}O_3Si$: 390.2590 **Found:** 390.2587

Similar procedure was followed to prepare **39a-exo**: **^{1}H-NMR** ($CDCl_3$) δ 0.01 (s, 3H), 0.03 (s, 3H), 0.86 (s, 9H), 0.96 (s, 3H), 0.98 (s, 3H), 1.25 (t, 3H, J=7 Hz), 1.4-2.6 (m, 6H), 3.35 (d, 1H, J=9 Hz), 4.1 (q, 2H, J=7 Hz), 4.88 (s, 1H), 5.08 (s, 1H), 5.26 (d, 1H, J=10 Hz), 5.32 (d, 1H, J=17 Hz), 5.42-5.55 (dd, 1H, J_1=17, J_2=10 Hz).

(1α, 6α)-8,8-Dimethyl-2β-carbethoxy-2α-vinyl-4-methylenetricyclo[4.3.0.0^{1,3}]nonane (39b) and Its 2α, 2β-Isomer (39b).

Methyltriphenylphosphonium bromide (1.34 g, 3.76 mmol) was dissolved with stirring in benzene (15 mL). Potassium tert-amylate/tert-amyl alcohol (3.76 ml, 3.76 mmol, 1.08 M) was then introduced via a syringe and the resulting yellow solution was stirred at room temperature for 20 min. The ketone **24b** (both isomers) (492 mg, 1.88 mmol) was then dissolved in 5 mL of benzene and added via a canula to the reaction mixture, which turned to a brownish-orange color. TLC showed no starting material after 2 h. The reaction was worked up with 20 mL of 1M HCl and extracted 3x with 20 mL of hexane, dried over $MgSO_4$, filtered, and evaporated to give 210 mg of crude material. The reaction mixture was then separated over flash silica (hexane→20% Et_2O: 80% hexane) to give one fraction (435 mg, 89.3%) which contained a mixture of endo and exo isomers in the same ratio as the starting ketone **24b**. The reaction was later repeated using each of the ketone isomers separately to obtain pure samples of each isomer.

39b-endo: R_f=0.44 (10% Et_2O, 90% hexane); b.p. 70°/0.05 mm Hg (Kugelrohr temp.) **IR** (neat) 3070, 1720, 1645 cm^{-1}; **^{1}H-NMR** ($CDCl_3$) δ 1.02 (s, 3H), 1.08 (s, 3H), 1.25 (t, 3H, J=7.1 Hz), 1.30 (dd, 1H, J_1=12.1, J_2=10.6 Hz), 1.62 (d, 1H, J=13.0 Hz), 1.67 (dd, 1H, J_1=12.1, J_2=7.5 Hz), 1.78 (d, 1H, J=13.8 Hz), 2.04-2.24 (m, 2H), 2.45-2.55 (m, 1H), 2.65 (s, 1H), 4.13 (q, 2H, J=7.2 Hz), 4.87 (s, 1H), 5.06 (s, 1H), 5.28 (dd, 1H, J_1=10.5, J_2=1.8 Hz), 5.32 (dd, 1H, J_1=17.5, J_2=1.8 Hz), 5.88 (dd, 1H, J_1=17.5, J_2=10.4 Hz); **^{13}C-NMR** ($CDCl_3$) δ 14.25 (CH_3), 29.36 (CH_3), 29.75 (CH_3), 38.42 (CH_2), 39.36(C), 39.37 (C), 42.96 (CH), 43.79 (CH_2), 45.22 (CH), 48.27 (CH_2), 53.44 (C), 60.62 (CH_2), 107.90 (CH_2), 120.18 (CH_2), 131.26 (CH), 151.50 (C), 171.25 (C); **Mass Spectrum** (70 eV, m/e (rel. int.)) 262 (20, M+), 261 (100), 245 (20), 233 (10), 215 (60), 187 (95), 171 (20), 161 (15), 145 (20), 131 (35), 119 (25), 109 (25).

Anal. Calcd $C_{17}H_{24}O_2$: C, 78.42; H, 9.29. **Found:** C, 78.43; H, 9.41.

39b-exo: R_f=0.39 (10% Et_2O, 90% hexane); b.p. 70°/0.05 mm Hg (Kugelrohr temp.); IR (neat) 3070, 1725, 1650, 1630 cm^{-1}; **^{1}H-NMR** ($CDCl_3$) δ 1.06 (s, 3H), 1.08 (s, 3H), 1.21-1.30 (m, 4H), 1.50 (d, 1H,

J=13.5 Hz), 1.67 (dd, 1H, J_1=12.2, J_2=7.3 Hz), 1.83 (d, 1H, J=13.5 Hz), 1.96 (s, 1H), 1.97 -2.17 (m, 2H), 2.65-2.75 (m, 1H), 4.18 (q, 2H, J=7.1 Hz), 4.87 (br.s, 1H), 5.04 (d, 1H, J=17.1 Hz), 5.06 (br. s, 1H), 5.07 (d, 1H, J=10.6 Hz), 5.51 (dd, 1H, J_1=17.2, J_2=10.8 Hz); **^{13}C-NMR** ($CDCl_3$) δ 14.12 (CH_3), 29.69 (CH_3), 30.23 (CH_3), 37.02 (CH_2), 39.14 (C), 42.49 (C), 43.33 (double intensity, CH, CH_2), 45.57 (CH), 48.13 (CH_2), 51.33 (C), 60.58 (CH_2), 107.76 (CH_2), 113.84 (CH_2), 136.07 (CH), 150.23 (C), 169.62 (C); **Mass Spectrum** (70 eV, m/e (rel. int.)) 262 (M^+, 10), 245 (5), 227 (10), 215 (14), 204 (10), 187 (100), 173 (10), 171 (13), 159 (10), 145 (10), 131 (25), 117 (14), 115 (12), 105 (12).

Anal. Calcd $C_{17}H_{24}O_2$: C, 78.42; H, 9.29. **Found:** C, 77.83; H. 9.26.

(E)-(1α, 6α)-8,8-Dimethyl-2β-carbethoxy-2α-vinyl-4-methoxymethylenetricylo[4.3.0.0^{1,3}]nonane (42b) and Its (E)-2α, 2β-(42b), (Z)-2β, 2α-(42b), and (Z)-2α, 2β-(42b) Isomers.

Methoxymethyltriphenylphosphonium chloride (1.21 g, 3.53 mmol) was treated with potassium tert-amylate (2.35 mL, 3.53 mmol, 1.5 M in tert-amyl alcohol) in 10 mL of benzene with stirring at room temperature resulting in a deep orange-red mixture. The mixture was stirred for 30 min, then ketone **24b** (185 mg, 0.706 mmol) was added in 5 mL of benzene via canula. TLC indicated s stantial starting material was left after 1 h at room temperature, so the reaction was heated to 50°C for 30 min at which time TLC indicated complete consumption of starting material with the appearance of 4 less polar spots. The reaction mixture was worked up with NH_4Cl, extracted with ether, dried over $MgSO_4$, and concentrated to give 960 mg of crude material. Filtration through a short column of flash silica (5 cm x 12 mm) with 10% EtOAc in hexane gave 78 mg (42%) of **42b** as a mixture of four diastereomers. The reaction was repeated on a pure sample **24b-endo** to give a mixture of **42b-endo-E** and **42b-endo-Z**; similarly, **42b-exo-E** and **42b-exo-Z** were obtained from **24b-exo**. The clean enol ethers proved to be unstable and decomposed completely within three to four days in $CDCl_3$ at -10°C.

42b-endo-E: R_f=0.68 (15% EtOAc in hexane); **^{1}H-NMR** ($CDCl_3$) δ 1.01 (s, 3H), 1.07 (s, 3H), 1.25 (t, 3H, J=7.1 Hz), 1.23-1.34 (m, 1H), 1.62 (d, 1H, J=14.0 Hz), 1.69 (ddd, 1H, J_1=12.7, J_2=8.3, J_3=0.8 Hz), 1.78 (d, 1H, J=13.8 Hz), 1.99 (ddd, 1H, J_1=17.5, J_2=8.6, J_3=2.5 Hz), 2.23 (dt, 1H, J_1=17.6, J_2=2.4 Hz), 2.47-2.58 (m, 1H), 2.58 (s, 3H), 4.12 (dq, 2H, J_1=7.1, J_2=1.1 Hz), 5.28 (dd, 1H, J_1=10.7, J_2=2.0 Hz), 5.31 (dd, 1H, J_1=17.6, J_2=2.0 Hz), 5.81 (dd, 1H, J_1=17.6, J_2=10.4 Hz), 6.07 (t, 1H, J=2.4 Hz); **^{13}C-NMR** ($CDCl_3$) δ 14.35 (CH_3), 29.35 (CH_3), 29.71 (CH_3), 33.90 (CH_2), 39.79 (C), 42.31 (CH), 43.32 (CH), 44.21 (CH_2), 48.73 (CH_2), 52.37 (C), 59.56 (CH_3), 60.61 (CH_2), 120.23 (CH_2), 120.55 (C), 131.56 (CH), 141.41 (CH), 171.54 (C).

42b-endo-Z: R_f=0.51 (15% EtOAc in hexane); not isolated in pure form. NMR data was obtained from a crude mixture. **^{1}H-NMR** ($CDCl_3$) δ 1.01 (s, 3H), 1.07 (s, 3H), 1.25 (t, 3H, J=7.1 Hz), 1.25-1.34 (m, 1H), 1.62 (d, 1H, J=14.0 Hz), 1.62-1.73 (m, 1H), 1.81 (d, 1H, J=14.0 Hz), 2.02-2.06 (m, 1H), 2.42-2.53 (m, 1H), 2.87 (s, 1H), 2.99 (s, 3H), 4.12 (q, 2H, J=7.1 Hz), 5.27 (dd, 1H, J_1=17.4, J_2=2.0 Hz), 5.28 (dd, 1H, J_1=10.5, J_2=2.0 Hz), 5.85 (dd, 1H, J_1=17.6, J_2=10.5 Hz), 5.96 (br. s, 1H).

42b-exo-Z: R_f=0.39 (15% EtOAc in hexane); **^{1}H-NMR** ($CDCl_3$) δ 1.05 (s, 3H), 1.07 (s, 3H), 1.18-1.24 (m, 1H), 1.27 (t, 3H, J=7.1 Hz), 1.49 (d, 1H, J=13.4 Hz), 1.63 (dd, 1H, J_1=11.9, J_2=7.3 Hz), 1.82

(d, 1H, J=13.5 Hz), 1.92 (ddd, 1H, J_1=16.6, J_2=7.7, J_3=2.1 Hz), 2.11 (dt, 1H, J_1=16.4, J_2=1.5 Hz), 2.21 (s, 1H), 2.62-2.72 (m, 1H), 3.58 (s, 3H), 4.17 (q, 2H, J=7.1 Hz), 5.04 (d, 1H, J=17.5 Hz), 5.05 (d, 1H, J=10.2 Hz), 5.55 (dd, 1H, J_1=17.6, J_2=10.3 Hz), 5.95-5.98 (m, 1H); ^{13}C-NMR ($CDCl_3$) δ 14.17 (CH_3), 29.76 (CH_3), 30.25 (CH_3), 33.04 (CH_2), 39.22 (C), 40.42 (CH), 42.92 (CH), 43.64 (CH_2), 48.12 (CH_2), 50.44 (C), 59.53 (CH_3), 60.48 (CH_2), 113.77 (CH_2), 119.13 (C), 136. 40 (CH), 141.38 (CH).

42b-exo-E: R_f=0.36 (15% EtOAc in hexane); ^{1}H-NMR ($CDCl_3$) δ 1.06 (s, 3H), 1.07 (s, 3H), 1.21-1.29 (m, 1H), 1.27 (t, 3H, J=7.2 Hz), 1.50 (d, 1H, J=13.4 Hz), 1.70 (dd, 1H, J_1=12.2, J_2=7.4 Hz), 1.80-1.93 (m, 3H), 2.32 (dt, 1H, J_1=17.7, J_2=1.9 Hz), 2.71-2.81 (m, 1H), 3.57 (s, 3H), 4.18 (dq, 2H, J_1=7.1, J_2=0.7 Hz), 5.01 (d, 1H, J=17.7 Hz), 5.04 (d, 1H, J=10.7 Hz), 5.50 (dd, 1H, J_1=17.2, J_2=10.8 Hz), 6.10 (t, 1H, J=2.4 Hz); ^{13}C-NMR ($CDCl_3$) δ 14.23 (CH_3), 29.58 (CH_3), 30.12 (CH_3), 32.36 (CH_2), 39.52 (C), 42.38 (CH), 43.63 (CH), 43.80 (CH_2), 48.83 (CH_2), 49.99 (C), 59.50 (CH_3), 60.54 (CH_2), 113.48 (CH_2), 119.63 (C), 136. 39 (CH), 141.38 (CH).

(5β,8α)-2α,2β-Dimethyl-9-carbethoxy-6-methoxymethylenetricyclo[6.3.0.0^{4,8}]undec-9-ene (43b).

In a procedure identical to the preparation of **40b** enol ether **42b** (mixture of isomers) (31 mg, 0.11 mmol) was pyrolyzed to give 15 mg (48%) of pyrolysate shown to consist of **43** (66%) and **44** (34%) each as a 1:1 mixture of E and Z isomers.

For **43:** ^{1}H-NMR ($CDCl_3$) δ 5.79 (m, 1H), 5.89 (m, 1H), 6.67 (t, 1H, J=2.3 Hz), 6.72 (t, 1H, J=2.3 Hz).

For **44:** ^{1}H-NMR ($CDCl_3$) δ 5.73 (m, 1H), 5.85 (m, 1H), 6.73-6.82 (m, 2H).

(1α,6α)-4,8,8-Trimethyl-2β-carbethoxy-2α-vinyltricyclo[4.3.0.0^{1,3}]non-4-ene (45b).

The exocyclic olefin **39b** (85 mg, 0.33 mmol) was dissolved in 5 mL of CH_2Cl_2 containing 18 mg of p-TsOH as a catalyst. The reaction mixture was stirred at room temperature for 8h, quenched with 2 mL of saturated $NaHCO_3$ solution, and extracted with CH_2Cl_2 (3x5 mL). The combined organic layers were dried (Na_2SO_4), filtered, and evaporated to give 71 mg (83.5%) of endocyclic olefin **45b:** ^{1}H-NMR ($CDCl_3$) δ 0.97 (s, 3H), 0.99 (s, 3H), 1.21 (t, 3H, J=7 Hz), 1.25-2.85 (m, 6H), 4.2 (q, 2H, J=7 Hz), 5.12 (m, 2H), 5.31 (bs, 1H), 6.1 (m, 1H).

(5β,8α)-2α,2β,6-Trimethyl-9-carbethoxytricyclo[6.3.0.0^{4,8}]undeca-6,9-diene(46b).

In a procedure identical to the preparation of **40b** endocyclic olefin **45b** (48 mg, 0.18 mmol) was pyrolyzed to give 36 mg (75%) of the pyrolysate which contained diene **46b** and Cope product **47b** in a ratio 20:80 as indicated by ^{1}H-NMR.

For **46b:** ^{1}H-NMR ($CDCl_3$) δ 1.0 (s, 3H), 1.01 (s, 3H), 1.25 (t, 3H, J=7 Hz), 1.3-1.55 (m, 2H), 1.6 (s, 3H), 1.82 (m, 1H), 2.15 (d, 1H), 2.3 (d, 1H), 2.45 (s, 1H), 2.6 (m, 1H), 3.05 (m, 1H), 3.15 (m, 1H), 4.18 (m, 2H), 5.15 (bs, 1H), 6.6 (t, 1H, J=2 Hz).

For **47b:** ^{1}H-NMR ($CDCl_3$) δ 6.3 (t, 1H, J=2 Hz).

(5β,8α)-2α,2β-Dimethyl-1α-[(tert-butyldimethylsilyl)oxy]-6-methylene-9-carbethoxytricyclo[6.3.0.0^{4,8}]undec-2-ene (40a).

A sample of cyclopropane **39a** (130 mg, 0.33 mmol) was evaporated (600°C (0.05 mm)) over five minutes through a horizontally situated Vycor tube (50 cm, 0.6 cm i.d.) which had been thoroughly

cleaned (nitric acid; 50% KOH) and pretreated with a slurry of $PbCO_3$. The pyrolysate was condensed in a trap cooled with liquid nitrogen. The apparatus was thoroughly washed with CH_2Cl_2; the solution was filtered to remove inorganic impurities, and the solvent was evaporated to give 115 mg of a light yellow oil shown to consist of triquinane **40a** (25%) and **41a** (75%). The mixture was separated by preparative TLC (silica gel) with 1% ethyl acetate in hexanes to give 35 mg (27%) of **40a** and 78 mg (60%) of **41a**. **40a**: R_f=0.51 (hexane/ethyl acetate, 19:1); **IR** (neat) 1710, 1250, 1110, 870, 830 cm^{-1}; **^{1}H-NMR** ($CDCl_3$) δ 0.01 (s, 3H), 0.03 (s, 3H), 0.87 (s, 9H), 0.99 (s, 3H), 1.06 (s, 3H), 1.27 (t, 3H, J=7 Hz), 1.57 (d, 1H, J=14 Hz), 1.97 (d, 1H, J=14, Hz), 2.25-2.35 (m, 3H), 2.65-2.91 (m, 3H), 3.31 (d, 1H, J=9.8 Hz), 4.16 (q, 2H, J=7 Hz), 4.85 (s, 1H), 4.91 (s, 1H), 6.68 (t, 1H, J=2.5 Hz); **^{13}C-NMR** ($CDCl_3$) δ -3.9 (CH_3), -3.8 (CH_3), 14.2 (CH_3), 18.1 (C), 23.9 (CH_3), 25.9 (CH_3), 29.8 (CH_3), 35.6 (CH_2), 40.2 (CH_2), 41.6 (C), 48.5 (CH_2), 52.2 (CH), 56.7 (CH), 59.9 (CH_2), 62.5 (C), 84.3 (CH), 107.4 (CH_2), 139.0 (C), 143.7 (CH), 157.8 (C), 164.5 (C); **Mass Spectrum** (70 eV, m/e (rel. int.)) 390 (2,M^+), 375 (3), 333 (100), 287 (20), 213 (40), 185 (20), 115 (20), 75 (60).

Calcd for $C_{23}H_{38}O_3Si$: 390.2590. **Found**: 390.2580.

41a: R_f=0.48 (hexane/ethyl acetate, 19:1); decomposed on silica; NMR data was obtained from a crude mixture of **40a** and **41a**: **^{1}H-NMR** ($CDCl_3$) δ 0.03 (s, 6H), 0.87 (s, 9H), 0.95 (s, 3H), 1.06 (s, 3H), 1.27 (t, 3H, J=7 Hz), 1.75 (d, 3H, J=7 Hz), 4.81 (d, 1H, J=2.5 Hz), 4.94 (d, 1H, J=2.5 Hz), 6.91 (q, 1H, J=7 Hz).

(5β,8α)-2α,2β-Dimethyl-9-carbethoxy-6-methylenetricyclo[6.3.0.0^{4,8}]undec-9-ene (40b).

A sample of **39b** (160 mg, 0.615 mmol) was evaporated (100°C, 10^{-4}mm) through a horizontally situated Vycor tube (41 cm, 5 mm i.d.) heated to 585°C after having been thoroughly cleaned (nitric acid; 50% KOH) and pretreated with a slurry of $PbCO_3$. The pyrolysate was condensed in a trap cooled with liquid nitrogen. The apparatus was thoroughly rinsed with pentane; the solution filtered to remove inorganic impurities, and the solvent evaporated to give 152 mg (95% mass balance) of orange oil shown by ^{1}H-NMR to consist of **40b** (43%) and **41b** (57%). The mixture was separated on preparative TLC plates (hexane/Et_2O, 9:3; 3 elutions) to obtain pure **40b** as an oil (59 mg, 36.9%) that solidified upon further purification by Kugelrohr distillation, and **41b** (71 mg, 44.4%), which had partially decomposed on silica.

40b: R_f=0.42 (10% Et_2O, 90% hexane); b.p. 45°/10^{-4} mm Hg (Kugelrohr temp.); **IR** (neat) 3055, 1705, 1650, 1620 cm^{-1}; **^{1}H-NMR** ($CDCl_3$) δ 1.08 (s, 3H), 1.15 (s, 3H), 1.17-1.38 (m, 4H), 1.62-1.72 (m, 2H), 1.96 (d, 1H, J=13.5 Hz), 2.23 (dd, 1H, J_1=15.9, J_2=1.4 Hz), 2.30-2.46 (m, 2H), 2.79-2.99 (m, 3H), 4.19 (q, 2H, J=7.1 Hz), 4.88 (2H, J=8.9 Hz), 6.70 (t, 1H, J=2.4 Hz); **^{13}C-NMR** ($CDCl_3$) δ 14.26 (CH_3), 29.65 (C), 30.12 (CH_3), 31.17 (CH_3), 31.28 (CH_3), 38.48 (CH_2), 39.43 (CH_2), 46.61 (CH), 48.11 (CH_2), 50.65 (CH_2), 55.44 (CH), 59.75 (CH_2), 69.59 (C), 106.59 (CH_2), 139.51 (C), 143.42 (CH), 158.50 (C), 164.67 (C); **Mass Spectrum** (70 eV, m/e (rel. int.)) 260 (M^+, 100), 245 (12), 232 (9), 214 (29), 199 (44), 187 (63), 171 (17), 159 (11), 145 (20), 131 (39), 115 (29), 105 (15), 91 (33), 77 (24), 69 (14).

Calcd for $C_{17}H_{24}O_2$: 260.1776. **Found**: 260.1777. **Anal. Calcd**: C, 78.42; H, 9.29. **Found**: C, 78.08; H, 9.29.

41b: R_f=0.39 (10% Et_2O, 90% hexane); ^{1}H-NMR ($CDCl_3$) δ 1.08 (s, 3H), 1.11 (s, 3H), 1.23 (t, 3H, J=7.1 Hz), 1.79 (d, 3H, J=7.0 Hz), 1.80-2.02 (m, 2H), 2.07 (br.s, 2H), 3.00 (br.s, 2H), 4.12 (q, 2H, J=7.1 Hz), 4.34 (br. s, 1H), 4.80 (q, 1H, J=1.2 Hz), 4.93 (q, J=1.2 Hz), 6.90 (q, 1H, J=7.0 Hz).

(5β,8α)-2α,2β-Dimethyl-1α-[(tert-butyldimethylsilyl)oxy]-9-carbethoxytricyclo[6.3.0.0^{4,8}]undec-9-en-6-one (26a).

a, By pyrolysis of **24a**:

In a procedure identical to the preparation of **40a** a sample of ketone **24a** (15 mg, 0.04 mmol) was pyrolysed to obtain 12 mg (80%) of the pyrolysate shown to consist of mainly the enone **27a** (>90%) and a trace amount of the ketone **26a**. For **27a**: R_f=0.18 (hexane/ethyl acetate, 15:1); IR (neat) 1712 cm^{-1}; ^{1}H-NMR ($CDCl_3$) δ 0.06 (s, 6H), 0.86 (s, 9H), 1.03 (s, 3H), 1.1 (s, 3H), 1.21 (t, 3H, J=7 Hz), 1.65 (d, 3H, J=9 Hz), 2.71 (m, 5H), 3.1 (m, 1H), 3.35 (d, 1H, J=9 Hz), 4.2 (q, 2H, J=7 Hz), 7.11 (q, 1H, J=9 Hz); ^{13}C-NMR ($CDCl_3$) δ -4.8 (CH_3), -4.2, 14.0 (CH_3), 15.9 (CH_3), 18.0 (C), 24.0 (CH_3), 25.6 (CH_3), 28.2 (CH_3), 41.3 (CH_2), 43.4 (CH), 49.9 (C), 60.6 (CH_2), 84.4 (CH), 142.7 (C), 151.8 (C), 169.5 (CH), 170.2 (C), 180.7 (C), 206.7 (C); Mass Spectrum (70 eV, m/e (rel. int.)) 393 (8, M+1), 336 (100), 289 (26), 215 (26), 214 (25), 202 (31), 111 (26), 75 (26), 73 (29).

b, By rearrangement of TMS enol ether **48a**:

In a procedure identical to the preparation of **26b** (procedure b), vinylcyclopropane **24a-exo** (0.22 g, 0.56 mmol) was converted to its corresponding TMS enol ether and subsequently pyrolyzed to obtain after hydrolysis 0.18 g (81%) of a mixture of the ketone **26a** and the Cope product **50a** in a ratio 15:85 as indicated by ^{1}H-NMR.

For **26a**: R_f=0.23 (hexane/ethyl acetate, 15:1); ^{1}H-NMR ($CDCl_3$) δ 0.02 (s, 3H), 0.03 (s, 3H), 0.87 (s, 9H), 1.03 (s, 3H), 1.12 (s, 3H), 1.28 (t, 3H, J=7 Hz), 1.68 (d, 1H, J=14 Hz), 2.06 (d, 1H, J=14 Hz), 2.2-2.8 (m, 5H), 3.12 (m, 1H), 3.36 (d, 1H, J=10 Hz), 4.2 (q, 2H, J=7 Hz), 6.69 (t, 1H, J=2.54 Hz), ^{13}C-NMR ($CDCl_3$) δ -4.0 (CH_3), -3.9 (CH_3), 14.2 (CH_3), 18.2 (C), 24.0 (CH_3), 25.9 (CH_3), 29.8 (CH_3), 34.7 (CH_2), 41.4 (CH_2), 41.7 (C), 48.0 (CH_2, CH), 59.1 (C), 59.4 (CH_2), 60.2 (CH), 86.8 (CH), 139.2 (C), 143.5 (CH), 163.8 (C), 221.9 (C).

For **50a**: R_f=0.18 (hexane/ethyl acetate, 15:1); ^{1}H-NMR ($CDCl_3$) δ -0.01 (s, 3H), 0.0 (s, 3H), 0.85 (s, 9H), 0.92 (s, 3H), 1.08 (s, 3H), 1.24 (t, 3H, J=7 Hz), 1.77 (d, 1H, J=14.3 Hz), 2.05 (d, 1H, J=14.3 Hz), 2.13 (d, 1H, J=19 Hz), 2.29-2.58 (m, 4H), 2.69 (m, 1H), 3.52 (d, 1H, J=10.2 Hz), 4.16 (m, 2H), 6.51 (t, 1H, J=3.6 Hz); ^{13}C-NMR ($CDCl_3$) δ -4.3 (CH_3), -4.1 (CH_3), 14.2 (CH_3), 18.0 (C), 25.8 (CH_3), 26.2 (CH_3), 30.5 (CH_3), 33.0 (CH_2), 42.0 (CH_2), 44.1 (C), 46.7 (CH_2), 49.0 (CH), 53.8 (CH), 57.1 (CH_2), 60.3 (C), 82.2 (CH), 134.9 (CH), 143.1 (C), 165.6 (C), 219.0 (C).

(5β,8α)-2α,2β-Dimethyl-9-carbethoxytricyclo[6.3.0.0^{4,8}]undec-9-en-6-one (26b).

a, By pyrolysis of **24b**:

In a procedure identical to the preparation of **40b**, ketone **24b** (0.44 g, 1.68 mmol) was pyrolyzed (540°C, 10^{-3} mm) to obtain 0.38 g (86.4%) of the pyrolysate shown to consist of mainly the enone **27b** (>90%) and a trace amount of the ketone **26b**. For **27b**: R_f=0.20 (hexane/ethyl

acetate, 6:1); ^{1}H-NMR ($CDCl_3$) δ 1.65 (d, 3H, J=9 Hz), 4.02 (q, 2H), 7.09 (q, 1H, J=9 Hz).

b, By rearrangement of TMS enol ether **48b**:

Vinylcyclopropane **24b-exo** or **24b-endo** (340 mg, 1.30 mmol) was dissolved in 10 mL of dry pentane at -20°C with stirring. To this was added 0.33 mL (1.6 mmol) of hexamethyldisilazane (HMDS). After 5 min at -20°C, 0.20 mL (1.4 mmol)of trimethylsilyl iodide was added and the resulting mixture stirred for 10 min at which time it was transferred to a test tube and centrifuged at 5000 rpm for 5 min to remove the white precipitate. The mother liquor was transferred with a pipet to a flask and evaporated to give 480 mg of crude material (TMS enol ether), which was evaporated at 100°C and 10^{-4} mm through a Vycor tube that had been pretreated with $PbCO_3$ and heated to 585°C. The crude pyrolysate was collected in a vacuum trap cooled with liquid N_2. It consisted of enol ethers **49b** and **50b**. The crude material was dissolved in 10 mL of CH_2Cl_2 to which was added 5 mL of 1N HCl. After stirring for 5 min, the organic layer was removed, and the aqueous layer was extracted 3x with 10 mL of CH_2Cl_2. The extact was combined with the first organic layer, dried over Na_2SO_4, filtered, and evaporated to give 292 mg (86%) of crude material. ^{1}H-NMR analysis of crude mixtures consistently showed that **24b-endo** gave a 1:20 ratio of tricycle **26b** to Cope product **50b**; whereas **24b-exo** gave a 1:3.7 ratio of these compounds. The crude mixtures were separated on preparative TLC plates using 20% ether in hexane (3 elutions) to give pure samples of each compound.

26b: R_f=0.45 (33% Et_2O in hexane); b.p. 80°C/10^{-4}mm Hg (Kugelrohr temp.); **IR** (neat) 1735, 1645 cm^{-1}; ^{1}H-NMR ($CDCl_3$) δ 1.11 (s, 3H), 1.22 (s, 3H), 1.25-1.39 (m, 1H), 1.32 (t, 3H, J=7.1 Hz), 1.76 (d, 1H, J=13.5 Hz), 1.93 (dd, 1H, J_1=12.3, J_2=6.5 Hz), 2.07 (d, 1H, J=13.2 Hz), 2.27 (d, 2H, J=5.9 Hz), 2.55-2.80 (m, 3H), 4.21 (q, 2H, J=7.2 Hz), 6.72 (t, 1H, J=2.7 Hz); ^{13}C-NMR ($CDCl_3$) δ 14.23 (CH_3), 30.88 (CH_3), 31.21 (CH_3), 34.47 (CH_2), 39.39 (C), 42.13 (CH), 43.45 (CH_2), 49.78 (CH_2), 49.97 (CH_2), 57.99 (CH), 60.07 (CH_2), 65.73 (C), 138.31 (C), 139.25 (C), 143.47 (CH), 163.87 (C); **Mass Spectrum** (70 eV, m/e (rel. int.)) 262 (M^+, 23), 245 (8), 232 (19), 214 (33), 186 (18), 149 (40), 129 (96), 123 (43), 112 (136), 91 (48), 55 (100).

Calcd for $C_{16}H_{22}O_3$: 262.1569. **Found**: 262.1570.

50b: R_f=0.40 (33% Et_2O in hexane); **IR** (neat) 1735, 1640 cm^{-1}; ^{1}H-NMR ($CDCl_3$) δ 1.01 (s, 3H), 1.10 (s, 3H), 1.22 (t, 3H, J=7.1 Hz), 1.26 (t, 1H, J=13.0 Hz), 1.58 (d, 1H, J=14.1 Hz), 1.64 (dd, 1H, J_1=13.0, J_2=6.9 Hz), 2.07 (d, 1H, J=14.1 Hz), 2.21-2.58 (m, 6H), 4.12 (dq, 2H, J_1=7.1, J_2=1.9 Hz), 6.49-6.52 (m, 1H); ^{13}C-NMR ($CDCl_3$) δ 14.13 (CH_3), 32.08 (CH_3), 32.63 (CH_3), 32.86 (CH_2), 39.19 (C), 43.85 (CH_2), 47.65 (CH_2), 50.05 (CH), 51.13 (CH), 52.00 (CH_2), 60.22 (CH_2), 134.96 (CH), 143.02 (C), 165.86 (C), 219.93 (C).

c, By ozonolysis of either **40b** or **43b**: Ozone was bubbled through 10 mL of CH_2Cl_2at -78°C until the solution turned blue. A portion of this (1.5 mL, 0.060 mmol) was then drawn into a graduated pipet which was precooled with liquid N_2 and quickly added to a stirred solution of ester **40b** (14.8 mg, 0.057 mmol) in 2 mL of CH_2Cl_2 which had been cooled to -78°C. After 30 min, 2 mL of dimethyl sulfide was added. The reaction was then warmed to room temperature and allowed to stir overnight

at which time it was concentrated under vacuum to give 14.2 mg of crude material. ^{1}H-NMR showed this material to consist of 30% of starting olefin **40b** and 70% of desired ketone **26b**.

(5β,8α)-2α,2β-Dimethyl-1α-[(tert-butyldimethylsilyl)oxy]-9α-carbethoxytricyclo[6.3.0.0^{4,8}]undecan-6-one (58a) and Its 9β-epimer (59b).

Unsaturated ester **26a** (24 mg, 0.06 mmol) was dissolved in 3 mL of methanol, 5 mg of PtO_2 was added, and the mixture was agitated on a Parr hydrogenator under 50 psi of H_2 for 12 h. Filtration and evaporation of the solvent gave 21 mg (87%) of a mixture of **58a** and **59a** in a ratio 80:20 as indicated by ^{1}H-NMR.

For **58a**: ^{1}H-NMR ($CDCl_3$) δ 0.02 (s, 3H), 0.03 (s, 3H), 0.85 (s, 9H), 0.90 (s, 3H), 0.98 (s, 3H), 1.22 (t, 3H), 1.4-1.82 (m, 11H), 3.29 (d, 1H, J=9 Hz), 4.18 (m, 2H).

For **59a**: ^{1}H-NMR ($CDCl_3$) δ 3.33 (d, 1H, J=10 Hz).

(5β,8α)-2α,2β-Dimethyl-9α-carbethoxytricyclo[6.3.0.0^{4,8}]undecan-6-one (58b) and Its 9β-epimer (59b).

Unsaturated ester **26b** (31 mg, 0.12 mmol) was dissolved in 2 mL of 95% EtOH, 3 mg of PtO_2 was added, and the mixture was agitated on a Parr hydrogenator under 40 psi of H_2 for 24 h. Filtration and evaporation of the solvent gave 27 mg (86.5%) of a mixture of **58b** and **59b** in a ratio 95:5 as indicated by GC analysis.

For 58b: IR (neat) 1735, 1710, 1620, 750 cm^{-1}; ;^{1}H-NMR ($CDCl_3$) δ 1.05 (s, 3H), 1.06 (s, 3H), 1.19-1.25 (m, 1H), 1.30 (t, 3H, J=7.2 Hz), 1.62-2.64 (m, 12H), 2.80-2.86 (m, 1H), 4.12 (q, 2H, J=7.2 Hz); ^{13}C-NMR ($CDCl_3$) δ 14.32 (CH_3), 29.40 (CH_2), 28.89 (CH_2, CH_3; double intensity), 30.18 (CH_3), 39.30 (C), 41.84 (CH), 42.67 (C), 45.97 (CH_2), 50.56 (CH_2), 56.17 (CH), 56.99 (CH_2), 60.32 (CH_2), 61.79 (CH), 173.9 (C).

(5β,8α)-2α,2β-Dimethyl-6-methylene-9α-carbethoxytricyclo[6.3.0.0^{4,8}]undecane (60b) and Its 9β-epimer (61b).

Unsaturated ester **60b** (15 mg, 0.058 mmol) was dissolved in 1.5 mL of methanol at room temperature with stirring. To this solution was added freshly scratched Mg (7 mg, 0.29 mmol, 70-80 mesh). Bubbles began to evolve almost immediately, and GC analysis of aliquots indicated that the reaction was complete after 95 min giving an 8:1 ratio of epimers with the ester preferentially in the α-position. The reaction mixture was then diluted with 10 mL of hexane and treated with 5 mL of 3M HCl. The layers were separated, and the aqueous solution was extracted 2x with 10 mL of hexane. The combined organic layers were then dried over Na_2SO_4, filtered and evaporated under vacuo to give 13.1 mg (87.3%) of **60b/61b** as an 8:1 mixture of inseparable epimers with the ester preferentially on the α-face: R_f=0.63 (1:10, ether-hexane); IR (neat) 1725, 1650 cm^{-1}.

major isomer: ^{1}H-NMR ($CDCl_3$) δ 0.98 (s, 3H), 1.02 (s, 3H), 1.17-2.73 (m, 16H), 4.16 (q, 2H, J=7.2), 4.85 (d, 2H, J=8.7 Hz); ^{13}C-NMR ($CDCl_3$) δ 14.34 (CH_3), 29.63 (CH_2), 30.13 (CH_3), 30.50 (CH_3), 33.96 (CH_2), 40.07 (CH_2), 46.39 (CH), 48.18 (C), 49.02 (CH_2) 55.83 (CH), 56. 83 (CH_2), 59.02 (CH), 59.94 (CH_2), 106.28 (CH_2);

minor isomer: ^{1}H-NMR ($CDCl_3$) δ 0.94 (s, 3H), 1.00 (s, 3H), 1.17-2.73 (m, 16H), 4.14 (q, 2H, J=7.1 Hz), 4.79 (br.s, 2H).

Epimerization at C-9. Sodium (5 mg) was added to 2 mL of dry EtOH and the resulting solution was allowed to stir for 1 h after which time all of the sodium had dissolved. Unsaturated ester **60b** (15 mg, 0.058 mmol) was dissolved in 0.5 mL of dry ethanol and added to the NaOEt/HOEt solution. A small aliquot worked up after 3 h indicated that the epimeric ratio remained unchanged. The mixture was then heated to reflux. Analysis of an aliquot after 1 h indicated that the reaction had reached an equilibrium ratio of 42:58 with the ester preferentially in the β-position. This ratio remained unchanged even after 24 h at reflux. The reaction mixture was worked up by partitioning it between 5 mL of hexane and 5 mL of 1N HCl. After separation of the hexane layer, the aqueous layer was extracted 2x with 5 mL of hexane. The combined organic layers were dried over Na_2SO_4, filtered and evaporated to give the crude epimerized ester. This mixture was separable on TLC using $AgNO_3$ impregnated silica and eluting 2 times with 1:10, ether-hexane (R_f: **60b**=0.56; **61b**=0.58).

(5β,8α)-2α,2β,6-Trimethyl-9α-carbethoxytricyclo[6.3.0.0^{4,8}]undec-6-ene (62b) and Its 9β-epimer (63b).

Esters **60b/61b**, (5.4 mg, 0.021 mmol) were dissolved in 1.5 mL of CH_2Cl_2 with stirring with a catalytic amount of p-TsOH. The mixture was stirred at room temperature for 24 h at which time the reaction was quenched with 2 mL of saturated aqueous $NaHCO_3$. The layers were separated, and the aqueous solution was extracted 2x with 10 mL of hexane. The organic layers were combined, dried over Na_2SO_4, filtered, and evaporated to give 5.3 mg (98%) of **62b/63b** as an 8:1 mixture of epimers that were inseparable on silica gel: R_f=0.63 (1:10, ether-hexane); IR (neat) 1725 cm^{-1}.
Major isomer: ^{1}H-NMR ($CDCl_3$) δ 0.97 (s, 3H), 0.99 (s, 4H), 1.25-1.33 (m, 3H), 1.47 (dd, 1H, J_1=12.7, J_2=9.6 Hz), 1.52-1.81 (m, 8H), 2.18 (d, 1H, J=13.0 Hz), 2.53-2.58 (m, 1H), 2.69-2.81 (m, 2H), 4.04-4.24 (m, 2H), 5.20 (br.s, 1H); ^{13}C-NMR ($CDCl_3$) δ 14.41 (CH_3), 27.25 (CH_2), 28.17 (CH_2), 28.33 (CH_3), 31.39 (CH_3), 40.19 (C), 45.60 (CH_2), 54.19 (CH), 54.71 (CH_2), 55.52 (CH), 56.68 (C), 59.81 (CH_2), 63.72 (CH), 131.47 (CH), 139.35 (C), 174.28 (C).
Minor isomer: ^{1}H-NMR ($CDCl_3$) δ 0.95 (s, 3H), 0.97 (s, 3H), 1.21-2.95 (m, 17H), 4.04-4.24 (m, 2H), 5.20 (br.s, 1H); ^{13}C-NMR ($CDCl_3$) δ 15.03 (CH_3), 28.82 (CH_2), 28.94 (CH_3), 29.66 (CH_2), 29.79 (CH_2), 30.36 (CH_3), 51.14 (CH_2), 59.18 (CH_2), 63.05 (CH), 129.05 (CH).

(5β,8α)-2α,2β-Dimethyl-6-methylene-9α-hydroxymethyltricyclo[6.3.0.0^{4,8}]undecane (66b) and Its 9β-epimer (67b).

Lithium aluminum hydride (14 mg, 0.37 mmol) was added to a dry solution of esters **60b/61b** (16 mg, 0.063 mmol) in 10 mL of dry THF and the mixture was stirred for 20 min after which time the reaction was quenched with 1 mL of water. The mixture was then extracted 3x with 5 mL of ether, and the combined organic layers were dried over Na_2SO_4, filtered, and evaporated to give 11 mg (79%) of crude alcohols **66b/67b** as a mixture of epimers whose ratio was the same as that of the starting ester: R_f=0.42 (ether-hexane, 3:1); IR (neat) 3310 br., 3060, 1650, 875 cm^{-1}; Mass

Spectrum (70 eV, m/e (rel. int.)) 220 (M^+, 15), 205 (12), 187 (28), 173 (5), 161 (24), 146 (28), 131 (100), 119 (22), 105 (32), 91 (42).

Cacld for $C_{15}H_{24}O$: 220.1827. **Found:** 220.1826.

Major isomer (66b): ^{1}H-NMR ($CDCl_3$) δ 1.00 (s, 3H), 1.02 (s, 3H), 1.20-2.80 (m, 13H), 3.58 (t, 1H, J=9.3 Hz) 3.76-3.85 (m, 1H), 4.84 (m, 2H); ^{13}C-NMR ($CDCl_3$) δ 30.42 (CH_3), 30.87 (CH_3), 33.7 (CH_2), 38.8 (C), 40.64 (CH_2), 43.65 (CH), 49.05 (CH_2), 57.47 (CH_2), 58.97 (CH), 64.08 (CH_2), 87.59 (CH_2), 159.03 (C).

Minor isomer (67b): ^{1}H-NMR ($CDCl_3$) δ 0.98 (s, 3H), 1.02 (s, 3H), 1.20-2.80 (m, 13H), 3.47 (t, 1H, J=9.3 Hz), 3.76-3.85 (m, 1H), 4.76 (m, 2H); ^{13}C-NMR ($CDCl_3$) δ 26.24 (CH_3), 29.34 (CH_3), 31.4 (CH_2), 58.27 (CH), 64.11 (CH_2), 87.00 (CH_2), 157.73 (C).

(5β,8α)-2α,2β-Dimethyl-6-methylene-9α-toluenesulfonylmethyltricyclo[6.3.0.0^{4,8}]undecane (68b) and Its 9β-epimer (69b).

Alcohols **66b/67b** (54 mg, 0.243 mmol) and p-toluenesulfonyl chloride (117 mg, 0.616 mmol) were dissolved in 1.5 mL of pyridine and stored at -5°C for 24 h after which time the solution was partitioned between 10 mL of hexane and 10 mL of 1M HCl. The organic layer was separated, and the aqueous layer was extracted 2x with 10 mL of hexane. The combined hexane solution was then dried over Na_2SO_4, filtered, and evaporated in vacuo to give 74.7 mg (78%) of crude material, which was filtered through silica gel with 10% Et_2O in hexane. ^{1}H-NMR indicated that the material was a 3:1 mixture of **68b/69b**, which was clean enough for the next reaction: R_f=0.72 (1:10, ether-hexane); IR (neat) 3060, 1650, 1660, 1595, 945, 825, 810, 720 cm^{-1}.

major isomer: ^{1}H-NMR ($CDCl_3$) : δ 0.93 (s, 3H), 0.99 (s, 3H), 1.03-2.35 (m, 12H), 2.45 (s, 3H), 2.58 (br.d, 1H, J=7.4 Hz), 3.99 (dd, 1H, J_1=9.5, J_2=7.9 Hz), 4.10-4.18 (m, 1H), 4.81 (br.d, 2H, J=8.7 Hz), 7.35 (d, 2H, J=8.2 Hz), 7.80 (d, 2H, J=8.2 Hz).

minor isomer: ^{1}H-NMR ($CDCl_3$) δ 0.89 (s, 3H), 0.98 (s, 3H), 1.03-2.35 (m, 12H), 2.45 (s, 3H), 2.58 (d, 1H, J=7.4 Hz), 3.88 (t, 1H, J=9.1 Hz), 4.10-4.18 (m, 1H), 4.75 (br.s, 2H), 7.35 (d, 2H, J=8.2 Hz), 7.80 (d, 2H, J=8.2 Hz).

(5β,8α)-2α,2β-Dimethyl-9α-bromomethyl-6-methylenetricyclo[6.3.0.0.^{4,8}]undecane (70b) and Its 9β-epimer (71b).

LiBr (59 mg, 0.68 mmol) was dissolved in 1.0 mL of dry acetone. The tosylates **68b/69b** (16.7 mg, 0.045 mmol) were then added at room temperature in 0.5 mL of dry acetone, and the solution was brought to reflux for 15 h after which time the solvent was removed in vacuo. The residue was partitioned between 10 mL of water and 10 mL of hexane. After separation of the organic layer, the aqueous layer was extracted 2x with 10 mL of hexane. The organic layers were combined, dried over Na_2SO_4, filtered, and evaporated to give 15.8 mg of crude material which was filtered through a plug of silica with ether-hexane (1:20) to give 8.4 mg (69%) of clean bromides **70b/71b** as a 3:1 mixture of epimers: R_f=0.68 (ether-hexane, 1:20), IR (neat) 3060, 880 cm^{-1}.

major isomer 70b: ^{1}H-NMR ($CDCl_3$) δ 1.01 (s, 3H), 1.03 (s, 3H), 1.04-2.70 (m, 13H), 3.32 (t, 1H, J=9.9 Hz), 3.58-3.63 (m, 1H), 4.83-4.87 (m, 1H).

minor isomer 71b: ^{1}H-NMR ($CDCl_3$): δ 0.98 (s, 3H), 1.03 (s, 3H), 1.04-2.70 (m, 13H), 3.25 (dd, 1H, J_1=15.5, J_2=9.9 Hz), 4.77-4.80 (m, 1H).

(5β,8α)-2α,2β,9α-Trimethyl-6-methylenetricyclo[6.3.0.0^{4,8}]undecane (72b) and Its 9α-epimer (73b).

Bromides **70b/71b** (5.2 mg, 0.018 mmol) were dissolved in 2 mL of THF and this solution was brought to reflux. Lithium aluminum hydride (6.8 mg, 0.18 mmol) was then added and the solution was refluxed for 15 min after which time it was cooled and slowly quenched with 5 mL of water. The aqueous solution was extracted 3x with 10 mL of hexane, and the combined organic solution was dried over Na_2SO_4, filtered through a plug of silica gel, and evaporated to give 2.8 mg (75%) of clean hydrocarbons **72b/73b** as a 3:1 mixture of epimers in favor of the unnatural diastereomer: R_f=0.80 (hexane).

Unnatural epimer 72b: ^{1}H-NMR ($CDCl_3$) δ 0.88-1.60 (m, 22H), 4.75 (br.s, 2H); ^{13}C-NMR ($CDCl_3$) δ 14.81 (CH_3), 29.68 (CH_2), 30.46 (CH_3, double intensity), 34.18 (CH_2), 35.44 (C), 39.65 (C), 40.84 (CH_2), 43.32 (CH), 45.03 (CH), 49.34 (CH_2), 56.85 (CH_2), 59.34 (CH), 105.36 (CH_2).

Natural epimer 73b: ^{1}H-NMR ($CDCl_3$) δ 0.88-1.60 (m, 22H), 4.80 (br.s, 2H); ^{13}C-NMR ($CDCl_3$) δ 14.05 (CH_3), 28.80 (CH_3), 31.23 (CH_2), 35.14 (CH_2), 38.51 (CH_2), 45.03 (CH), 44.61 (CH_2), 48.33 (CH), 58.33 (CH), 105.36 (CH_2).

(±)-Pentalenene (1) and Epipentalenene (4a).

p-Toluenesulfonic acid (5 mg, 0.0263 mmol) was added to hydrocarbon **72b/73b** (2 mg, 0.01 mmol) in 1 mL of CH_2Cl_2, and the mixture was stirred at room temperature for 24 h after which time the reaction was quenched with 1 mL of 3N HCl. The mixture was extracted 3x with 5 mL of hexane. The combined layers were dried over Na_2SO_4, filtered through a plug of silica gel, and evaporated to give a near quantitative yield of (±)-pentalenene (**4**) and epipentalene (**4a**) as a 1:3 mixture respectively. ^{1}H-NMR of the mixture contains peaks which match those in the spectra of each of the authentic compounds.

For **1**: ^{1}H-NMR ($CDCl_3$) δ 5.16 (br s, 1H), 2.7-2.6 (m, 1H).

For **4a**: ^{1}H-NMR ($CDCl_3$) δ 5.18 (br s, 1H), 2.96-2.75 (m, 1H).

(5β,8α)-2α,2β-Dimethyl-1α-[(tert-butyldimethylsilyl)oxy]-6-methylene-9α-carbethoxytricyclo[6.3.0.0^{4,8}] undecane (60a).

To a solution of the α,β-unsaturated ester **40a** (100 mg, 0.26 mmol) in 5 mL of dry methanol was added 33 mg of dry magnesium turnings. After 30 min, a cloudy mixture formed, which was stirred for 3 h. Ether (10 mL) was added, the mixture was cooled in an ice bath, and excess Mg was destroyed by careful addition of 3N HCl. The ether layer was separated and the aqueous layer extracted with ether (2x5 mL). The combined organic extracts were washed with saturated NaCl solution and dried over $MgSO_4$. Evaporation of the solvent yielded crude material, which was filtered through a 1" plug of silica gel with 5% ethyl acetate in hexanes to obtain 98 mg (97.5%) of **60a**. Analytical data for **60a** was as follows: R_f=0.51 (hexane/ethyl acetate, 19:1); IR (neat) 1715, 1250, 1110, 890, 850 cm^{-1}; ^{1}H-NMR ($CDCl_3$) δ -0.05 (s, 3H), -0.03 (s, 3H), 0.80 (s, 3H), 0.81 (s, 9H), 0.86 (s, 3H), 1.21 (t, 3H, J=7 Hz), 1.59-2.65 (m, 11H), 3.14 (d, 1H, J=9 Hz), 4.09 (q, 2H,

J=7 Hz), 4.75 (s, 1H), 4.79 (s, 1H); **^{13}C-NMR** ($CDCl_3$) δ -4.0 (CH_3), -3.8 (CH_3), 14.2 (CH_3), 18.2 (C), 22.4 (CH_3), 25.9 (CH_3), 28.4 (CH_3), 30.5 (CH_2), 43.2 (CH_3), 37.6 (CH_3), 41.4 (C), 52.8 (CH), 54.2 (CH_2), 57.1 (CH), 58.6 (C), 60.0 (CH_2), 60.6 (CH), 84.8 (CH), 106.7 (CH_2), 156.7 (C), 174.4 (C); **Mass Spectrum** (CI, m/e (rel. int.)) 393 (11, M^+), 335 (30), 261 (100), 215 (25), 133 (35), 85 (75).

Calcd for $C_{19}H_{31}O_3Si$ (M-57): 335.2042. **Found:** 335.2047.

Epimerization at C-9. In a procedure identical to the preparation of **61b** ester **60a** (25 mg, 0.06 mmol) was epimerized to obtain an inseparable mixture of **61a** and **60a** in a ratio 3:2 as indicated by ^{1}H-NMR.

Major isomer (C-9β): **^{1}H-NMR** ($CDCl_3$) δ 3.11 (d, 1H, J=9 Hz), 4.70 (bs, 1H).

(5β,8α)-2α,2β-Dimethyl-1α-[(tert-butyldimethylsilyl)oxy]-6-methylene-9α-hydroxymethyltricyclo[6.3.0.0^{4,8}] undecane(66).

To a solution of the ester **60a** (45 mg, 0.11 mmol) in 3 mL of THF was added lithium aluminum hydride (50 mg, 1.3 mmol), and the mixture was stirred for 1 h. The flask was cooled in an ice bath, and 50 μL of water was added, followed by 50 μL of 10% KOH, then 150 μL of water. The white granular precipitate formed was filtered off and the filtrate passed through a 1" plug of anhydrous $MgSO_4$. Evaporation of the solvent yielded **66** as a colorless oil: 38 mg, 100%; R_f=0.46 (hexane/ethyl acetate, 3.1); **IR** (neat) 3500, 1670, 1110, 890, 820 cm^{-1}; **^{1}H-NMR** ($CDCl_3$) δ 0.03 (s, 3H), 0.06 (s, 3H), 0.88 (s, 9H), 0.90 (s, 3H), 0.96 (s, 3H), 1.5-2.73 (m, 11H), 3.4 (d, 1H, J=5 Hz), 3.6 (bs, 1H), 3.72 (m, 2H), 4.76 (s, 1H), 4.79 (s, 1H).

For **C-9β isomer:** **^{1}H-NMR** ($CDCl_3$) δ 3.21 (d, 1H, J=8 Hz), 4.71 (s, 1H), 4.76 (s, 1H).

(5β,8α)-2α,2β,9α-Trimethyl-1α-[(tert-butyldimethylsilyl)oxy]-6-methylenetricyclo [6.3.0.0^{4,8}]undecane (72).

To a solution of the alcohol **66** (38 mg, 0.11 mmol) in 3 mL of CH_2Cl_2 at 0°C was added triethylamine (0.08 mL, 5.5 mmol) followed by methanesulfonyl chloride (0.21 mL, 2.75 mmol). The orange-colored mixture o tained was allowed to warm to room temperature over a period of 3 h, then it was diluted with 5 mL of ether and poured into 3 mL of ice-cold water. The organic layer was separated, and the aqueous layer was extracted with ether (2x3 mL). The combined extracts were washed with saturated $NaHCO_3$, brine, dried over $MgSO_4$, and solvent evaporated to obtain the mesylate **68**: 41 mg, 90%; **^{1}H-NMR** ($CDCl_3$) δ 0.01 (s, 3H), 0.02 (s, 3H), 0.87 (s, 9H), 0.89 (s, 3H), 0.93 (s, 3H), 1.25-2.6 (m, 11H), 2.98 (s, 3H), 3.25 (d, 1H, J=8 Hz), 4.12 (t, 1H, J=9.3 Hz) 4.32 (m, 1H), 4.82 (s, 1H), 4.86 (s, 1H).

To a solution of the mesylate (41 mg, 0.1 mmol) in 1.5 mL of THF was added lithium triethylborohydride (0.5 mL, 0.5 mmol, 1 M in THF), and the mixture stirred for 18 h. The flask was cooled in an ice bath, and excess hydride was quenched by dropwise addition of water. The organoboranes were oxidized by adding 0.2 mL of 10% aqueous KOH, followed by the dropwise addition of 0.2 mL of 30% aqueous H_2O_2. The ice bath was removed, and the reaction mixture was heated to 50° for 30 min. The white precipitate formed was filtered and the filtrate extracted with ether (2x4 mL). The combined extracts were washed with brine, dried over $MgSO_4$ and solvent evaporated to

give 32 mg (97%) of the product **72**: R_f=0.57 (3% ether in hexane); **IR** (neat) 1640, 1460, 1250, 1110, 890, 850 cm^{-1}; **^{1}H-NMR** ($CDCl_3$) δ 0.01 (s, 3H), 0.03 (s, 3H), 0.86 (s, 3H), 0.88 (s, 9H), 0.91 (s, 3H), 0.96 (d, 3H, J=7 Hz), 1.1-2.45 (m, 11H), 3.23 (d, 1H, J=9 Hz), 4.76 (s, 1H), 4.8 (s, 1H); **^{13}C-NMR** ($CDCl_3$) δ -4.1 (CH_3), -3.8 (CH_3), 15.0 (CH_3), 18.2 (C), 23.0 (CH_3), 26.0 (CH_3), 28.4 (CH_3), 34.1 (CH_2), 35.4 (CH_2), 38.5 (CH_2), 41.5 (C), 42.6 (CH), 50.3 (CH), 54.3 (CH_2), 58.3 (C), 60.7 (CH), 85.5 (CH), 105.7 (CH_2), 158.6 (C); **Mass Spectrum** (70 eV, m/e (rel. int.)) 277 (50), 201 (12), 161 (14), 133 (7), 119 (9), 91 (8), 75 (100).

Calcd for $C_{21}H_{38}OSi$: 334.2691. **Found:** 334.2689.

For **C-9β isomer**: **^{1}H-NMR** ($CDCl_3$) δ 3.17 (d, 1H, J=9 Hz), 4.71 (s, 1H), 4.73 (s, 1H).

(5β,8α)-2α,2β,9α-Trimethyl-1α-[(tert-butyldimethylsilyl)oxy]tricyclo[6.3.0.0^{4,8}]undecan-6-one (74).

To a solution of the olefin **72** (mixture of epimers, 15 mg, 0.045 mmol) in 2 mL of THF/water (1:1) was added a small crystal of OsO_4 followed after 10 min by sodium periodate (19 mg, 0.009 mmol). The mixture was stirred at room temperature for 12 h, then it was diluted with 3 mL of ether and poured into 2 mL of water. The organic layer was separated and the aqueous layer was extracted with ether (2x1 mL). The combined extracts were washed with saturated aqueous $NaHSO_3$ (1x1 mL), dried over $MgSO_4$ and solvent evaporated. The crude material was chromatographed on silica gel with 1% ethyl acetate in hexane to obtain the ketone **74**: 12 mg (80%); **IR** (neat) 1720, 1110 cm^{-1}.

Major isomer (C-9β): **^{1}H-NMR** ($CDCl_3$) δ 0.01 (s, 3H), 0.03 (s, 3H), 0.86-0.96 (m, 18H), 1.4-2.5 (m, 11H), 3.18 (d, 1H, J=9 Hz).

Minor isomer (C-9α): **^{1}H-NMR** ($CDCl_3$) δ 3.21 (d, 1H, J=9 Hz).

Pentalenic Acid Methyl Esters (76/77)

(a) Preparation of the enol triflates: To a solution of the ketone **74** (12 mg, 0.036 mmol) in 1 mL of CH_2Cl_2 was added 2,6-di-tert-butyl-4-methylpyridine (8 mg, 0.04 mmol) and trifluoromethanesulfonic anhydride (7 μL, 0.038 mmol). The mixture was stirred at room temperature for 12 h, at the end of which it turned dark brown. The solvent was evaporated, and the residue was treated with 2 mL of pentane. The insoluble material was removed by centrifugation. The pentane layer was washed with 1 mL of ice-cold 3N HCl, dried over K_2CO_3, and evaporated to obtain the triflates: 12 mg; 72%; **^{1}H-NMR** ($CDCl_3$) δ 3.29 (bd), 5.62 (t, 1H, J=2 Hz, for major isomer), 5.70 (bs, 1H, for minor isomer).

(b) Pentalenic acid methyl esters: A mixture of triflates (12 mg, 0.026 mmol), triethylamine (7.5 μL, 0.052 mmol), palladium acetate (1 mg, 0.004 mmol), triphenylphosphine (3 mg, 0.011 mmol) and methanol (0.1 mL, 2.5 mmol) in DMF (0.15 mL) was purged with carbon monoxide for 5 min and stirred under a CO balloon at room temperature for 14 h. Ether (2 mL) and water (1 mL) were then added. The ether layer was washed with water (2 x 1 mL) dried over $MgSO_4$, and evaporated. The residue (8 mg) was subjected to PTLC (3 x 4") using 0.5% ethyl acetate in hexane as the eluant (4 elutions) to obtain an inseparable mixture of pentalenic acid methyl esters **76** and **77**.

For **76**: **^{1}H-NMR** ($CDCl_3$) δ 3.43 (d, 1H), 3.71 (s, 3H), 6.82 (m, 1H).

For **77**: **^{1}H-NMR** ($CDCl_3$) δ 6.87 (m, 1H).

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43. For a review see: Hudlicky, T.; Kutchan, T. M.; Naqvi, S. M. Org. React. **1985** 33, 247.

44. Conditions adapted from the synthesis of isocomenic acid: Short, R. P.; Ranu, B, C.; Revol, J-M.; Hudlicky, T. J. Org. Chem. **1983**, 48, 4453.

45. Hudlicky, T.; Koszyk, F. J. Tetrahedron Lett. **1980**, 2487.

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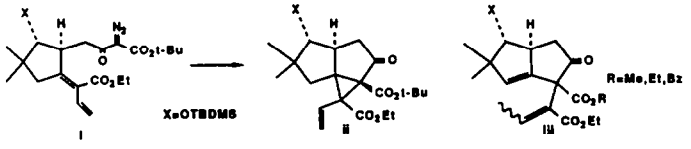
49. Diazo keto esters **30** and **31** were prepared by condensation of the corresponding lithio diazo esters generated at low temperatures with acid chloride of acid **22**. The procedure was adapted from: Schöllkopf, U.; Frasnelli, H. Angew. Chem. Int. Ed. Engl. **1970**, 9, 301. Benzyl diazo acetate was prepared according to procedure adapted from: Ledon, H.; Linstrunelle, G.; Julia, S. Tetrahedron **1973**, 29, 3609. (see also ref. 47) A representative procedure for the preparation of t-butyl diazo keto ester **i** is given here: Lithium diisopropylamide was generated from 50 mg (0.5 mmol) of diisopropyl amine in 3 mL of dry THF using n-BuLi in hexane (freshly titrated). This solution was added dropwise to a THF solution of t-butyl diazo acetate (71 mg, 0.5 mmol) cooled to -100°C (hexane/ liq. nitrogen bath). This diazo ester was in turn prepared according to procedures used in the diazo transfer reactions of β-keto esters (ref. 47). After the addition, the reaction was stirred at -100°C for 15 min whereupon the acid chloride of **22** (generated from 200 mg (0.5 mmol) of **22** and 100 mg of $(COCl)_2$) was added in THF. The reaction mixture was allowed to warm up to -10° (2 h) and quenched with HOAc/THF, diluted with Et_2O, and neutralized with $NaHCO_3$. After extraction and evaporation, the crude oil was filtered through alumina to give 150 mg (58%) of diazo keto ester **i** as an oil. Other compounds of this type were prepared by the same method: methyl ester: <10%; ethyl ester: <20%; benzyl ester 37%.
Vinylcyclopropanes **ii**, **33**, and **34** were prepared in 47%, 54% and 79% yield respectively by the procedure described in this paper for the preparation of **24**.
Pyrolyses were carried out as described for **24** and the mixtures were analyzed by ^{1}H-NMR and GC. The results of pyrolyses are sumarized below:

cyclopropane	26	27	iii
ii	5%	95%	---
33	~15%	---	85%
34	~20%	---	70%



The low yield of **26** in the case of benzyl ester may be due to low volatility. All compounds were characterized by spectral means.

50. The t-butyl ester **i** was also prepared and converted to cyclopropane **ii**, but the pyrolysis of **ii** gave only slightly improved results over those of cyclopropane **24**. Presumably, the conditions of pyrolysis generate **24** by thermal cleavage of t-butyl group. This event takes place before any radical cleavage of cyclopropane ring.

51. Prepared by condensation of **51** with acid chloride of **22**.

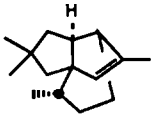
52. Preparation of **51**: 2-methoxyethyl amine was converted to its N-nitroso derivative and this reagent stored. The nitrosation followed the preparation of diazomethane described in Org. Syntheses Coll. Vol II **1943**, 165.

53. Research on application of this reaction to the synthesis of homologated enol ethers is in progress.

54. This reaction was performed in the pentalenene series only.

55. Several attempts were made at functionalization of this carbon in the pentalenic acid series. In our hands, the following scheme, performed according to a published procedure,[6c] did not yield pentalenic carboxaldehyde.

56. The discovery of the Cope rearrangement was made in a fortuitous way. Initially, we had thought that the pyrolysis of **45b** gave only **46b**, since the ^{1}H-NMR Spectrum indicated a triplet at ~6.5 and a smaller signal at 6.72 ppm. We assumed that these signals compared to **46b** and its C-5 isomer and carried the major product through reductive operations to the final comparison with pentalenene. It was at this stage that a structure **i** was assigned to the hydrocarbon, and the correct structure **47b** assigned to the product of pyrolysis. The small signal at 6.72 ppm corresponded to the triquinane **46b**.



i

57. The necessary enone precursor to cyclopropane **52** is available by the Weiss/Cook reaction: Weiss, U.; Edwards, J.-M. Tetrahedron Lett. **1968**, 4885; see also: Han, W. C.; Takahashi, K.; Cook, J. M.; Weiss, U.; Silverton, T. F. J. Am. Chem. Soc. **1982**, 104, 318.

58. For preliminary account see: Fleming, A.; Sinai-Zingde, G.; Natchus, M. G.; Hudlicky, T. Tetrahedron Lett. **1987**, 167.

59. Only the E-iodide undergoes cyclizations under these conditions. The ratio of E/Z can be improved by using $TiCl_4$/TMSI.

60. In the isocomene series this hydrogenation produced the epi configuration to the tune of 100%, contrary to the report by Chatterjee (Chatterjee, S. J. Chem. Soc. Chem. Comm. **1979**, 620). Base catalyzed isomerization led to the natural configuration (100%). This equilibration has been exploited in the synthesis of isocomenic acids (ref. 44) and isocomenes (ref. 12j).

61. Repetition of Chatterjee's work yielded epi-isocomene, as confirmed by comparison of final products: Kwart, L. D.; Tiedje, M. Frazier, J. O.; Hudlicky, T. Syn. Commun. **1986**, 16, 393.

62. The Conia-Dauben modification was used. See for example: Conia, J. M.; Limasset, J. Bull. Soc. Chim. Fr. **1967**, 6, 1936; ref. **12g**, **12j**, **44**.

63. The procedures were adapted from similar reductions of acrylonitriles and acryloamides and found selective in approximately 12 cases: Hudlicky, T.; Sinai-Zingde, G.; Natchus, M. G. Tetrahedron Lett. **1987**, in press.
For the original procedures see: Profitt, J. A.; Watt, D. S.; Corey, E. J. J. Org. Chem. **1975**, 40, 127; Brettle, R.; Shibib, S. M. J. Chem. Soc. Perkin Trans I **1981**, 2912.

64. These reductions were not optimized. It would seem that the diastereoselectivity should improve upon lowering the temperature of these reductions. The keto-acrylate **26** also underwent a reduction, but the product was contaminated with the corresponding C-6 alcohol. The crude reaction mixtures were titrated with Jones reagent to provide >90% yield of keto esters **58** and **59**.

65. This approach utilized all available routes to the triquinanes and allowed them to be interconvertible through Wittig/ozonolysis transformations. Future syntheses should utilize exocyclic enol ethers for pyrolyses since these compounds give highest yields of triquinanes which provide triquinanes **26** by ozonolysis.

66. See references on biosynthetic cationic cyclizations, enone reductions of ring C and other functionalizations (**7a, b, c, f; 20**).

67. Cuprate additions to β-enone carbon at C-9 gave epi configurations of C-9 methyl as did reductions of β-methyl enones with metals. Hydride reductions gave mixtures in which C-9 unnatural epimer was the major product (ref. **7c**) These observations led to the initial belief that the natural product possessed the less stable configuration at C-9.

68. The MM/2 program and IBM-PC were used in these calculations.

69. The calculations were performed on pentalenene series only.

70. That the angular methyl group restricts the inside space of ring B/C diquinane became apparent during hydrogenations of acrylates in the isocomene series (ref. **12j**, **44**, **61**). That the C-8 hydrogen poses no special hindrance in the inside cavity of pentalenene was borne out by Paquette's cuprate additions to C-9 (to the β-carbon of enone) (ref. **7c**).

71. The esters possessing the exocyclic methylene at C-6 are the compounds most easily separated. Hydrocarbons have been separated using preparative GC but in our hands this proved difficult. Thin layer chromatography ($AgNO_3$) of **60** and **61** should serve as the means of separation and recycling in both series.

72. Cacchi, S.; Morera, E.; Ortar, G. Tetrahedron Lett. **1985**, 26, 1109.

73. (a) Jardine, F. H. Prog. Inog. Chem. **1981**, 28, 63. (b) Walborsky, H. M.; Allen, L. E. J. Am. Chem. Soc. **1971**, 93, 5465.

74 Becker, K. B.; Geisel, M.; Brob, C. A.; Kuhnen, F. Synthesis **1973**, 493.

75. The only evidence of stability of C-9 radicals comes from reductions of ring C enones (ref. **7c**).

76. From the data base gathered so far it is possible to judge the stereochemistry at three adjacent centers (C-9, C-4, C-5) from the shifts of methyl substituent at C-9 (see references **7h**, **12j**, **34**, **43**, **44**, **46**, **47**, **48**).