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Synthesis of Rings DEF of Solanoeclepin A

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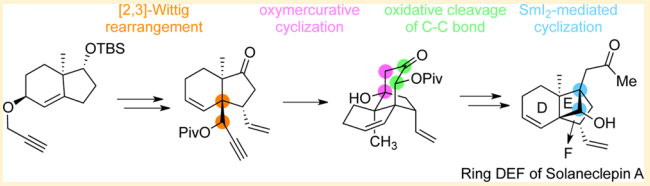
Supporting Information

ABSTRACT: An improved synthesis of rings DEF of solanoeclepin A has been achieved from *ent*-Hajos Parrish ketone. A key tricyclo[5.3.2.0^{1,6}]decene intermediate having an additional vinyl group as a precursor of a hydroxyl functionality was synthesized, in which the key steps included (i) a [2,3]-Wittig rearrangement to provide *trans*-hydroindene with C11(*R*)-configuration, (ii) the introduction of a vinyl group as a masked OH at C6, (iii) an oxymercurative aldol to synthesize the tricyclo[5.3.2.0^{1,6}]decene moiety, (iv) an oxidative C−C bond cleavage to yield an aldehyde and an unsaturated methyl ketone, and (v) a radical cyclization for the cyclobutane ring formation to provide the tricyclo[5.2.1.0^{1,6}]decene compound.



INTRODUCTION

The production of sufficient crops by agriculture is an urgent priority in the current century for feeding an increasing global population. To address this need, both the development of high-yielding and robust crops, as well as effective means to control pest and plant diseases are important areas of research.

This article deals with a synthetic effort that contributes to solving this problem through the possible chemical control of a pest, the potato cyst nematode, which severely damages the potato crop. This nematode is very resistant to typical pest control methods because it can survive for many years in the soil by keeping the eggs in a hard capsule (cyst). In 1999, solanoeclepin A (**1**) was identified by H. Schenk as the natural chemical messenger that stimulated the hatching of the eggs of the potato cyst nematodes *Globodera rostochiensis* (Woll.) and *G. pallida* (Stone) to larvae and to exit from the capsule.[1] Once the larvae are in the soil, they die in a few weeks if the host plant potato roots are unavailable. Therefore, the administration of **1** in the winter prior to the planting of the crops could be an effective means to eradicate this pest. Similar attempts for cyst nematode control had been reported in 1982 by T. Masamune, who isolated glycinoeclepin A (**2**) and elucidated its correct structure from a trace amount of the substance, and identified it as the stimulant for the hatching of the soybean nematode *Heterodera glycins* (Ichinohe) (Figure 1).[2] Subsequently, four total syntheses of **2** were achieved by different groups led by A. Murai, E.J. Corey, H. Watanabe, and K. Tanino, and its application in agriculture is now in progress.[3] On the other hand, only one total synthesis of **1** has been reported by K. Tanino,[4] although an elegant partial synthesis has also been published by Hiemstra.[5]

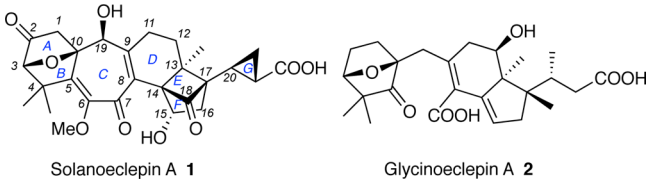


Figure 1. Structure of solanoeclepin A and glycinoeclepin A.

We became interested in the total synthesis of solanoeclepin A (**1**) and decided to explore several synthetic strategies to assemble the heptacycic ring system. Our first approach to the cyclobutane ring E was an exoselective intramolecular opening of an epoxide by a sulfonyl carbanion, which was generated as a result of a conjugate addition to α−silyl-vinylsulfone, via HADCA chemistry.[6] Since this method could not eventually provide the entire tricyclo[5.2.1.0^{1,6}]decene ring system of **1**, we developed a cyclization under acidic conditions, from an allyltrimethylsilane nucleophile and a Nicholas type carbocation electrophile, to form the core rings D, E, and F.[7] In our further studies to simplify the route,[8] we have also explored a radical cyclization method[9] for cyclobutane ring closure, and have successfully synthesized the DEF tricyclic array. We have also reported the synthesis of rings ABC of **1** from a simple cyclohexanone as a model of ring D of **1**.[10] Herein, we describe our further progress toward the total synthesis of **1**, in which we have also introduced a vinyl group at the C15 position of **1** as a precursor for the C6-OH of **6** in ring F (Figure 1).

Retrosynthetic Analysis. We have recently published the partial synthesis of both the ABC and DEF polycyclic arrays[8,10] of solanoeclepin A, based on our unique retrosynthetic analysis of **1** (Scheme 1) which disconnects at C_9-C_{19} and C_7-C_8 (numbering of **1** from Schenk[1]) of the cycloheptadienone ring C. Our model studies found that a successful and stereoselective cyclization to yield cyclopeantadienol **3** could be achieved through a cobalt-assisted Prins cyclization of **4**,[10] which in turn could be assembled by a coupling of two subunits **5** (rings AB) and **6** (rings DEFG).[11]

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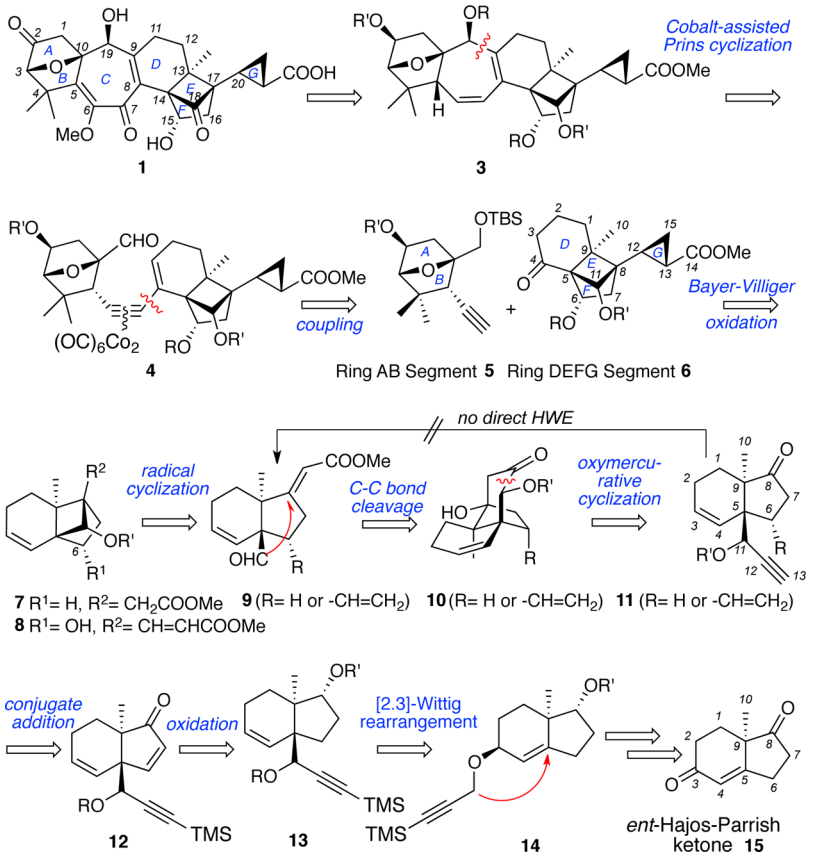
Scheme 1. Retrosynthesis of Solanoeclepin A



Based on our previous work on model compound **7**,[8] we decided to employ a radical cyclization of **9** (R = vinyl) as the key reaction for synthesizing the cyclobutane subunit in the tricyclo[5.2.1.0^{1,6}]decene **8**. The installation of the equivalent of a hydroxyl group at the C15 position of **1** or C6 of **6** was necessary, since a hydroxyl group itself could potentially suffer dehydration, being at a beta position with respect to the carbonyl group of the cyclopentanone unit in intermediate **11**.[8] Thus, a vinyl group was introduced instead in **9** ∼ **11** (R^1= −CH═CH$_2$), which would be unmasked as a hydroxyl group via a Baeyer−Villiger oxidation of the methyl ketone derived from the vinyl group. We have found that ketone **11** (R = H) could not be directly converted to **9** via a HWE olefination, because both faces of the carbonyl group were found to be too hindered as well as the propensity of the carbonyl group to enolize. We would solve this problem through the intermediacy of tricyclic **10**, which may be obtained by an intramolecular oxymercurative aldol reaction from **11**. The conjugate addition of vinylcuprate to enone **12** would provide **11** (R = vinyl). Enone **12** would be obtained from compound **13** (R = MOM). We have already reported the synthesis of the *trans*-fused perhydroindenone **13** via a [2,3]-Wittig rearrangement from allylic propargylic ether **14**, derived from *ent*-Hajos-Parrish ketone **15**.[8]

RESULTS OF SYNTHESIS

Synthesis of Tricyclo[5.3.2.0^{1,6}]decene Ring Intermediates 27 and 28. As shown in Scheme 1 we employed **16** as the starting material, whose synthesis from *ent*-Hajos-Parrish ketone **15** in five steps and an overall 25.9% yield has already been reported in our previous article.[8] A one-pot two-step [2,3]-Wittig rearrangement of **16** afforded exclusively C11-(*R*)-propargylic alcohol **17** in 85% yield as a single stereoisomer (Scheme 2). Anticipation that strongly basic reagents, such as LDA, would be employed later, the C11-OH was protected as a MOM[12] ether to provide **18**. Selective *O*-desilylation under acidic conditions was carefully administered using 0.75% HCl/MeOH at 0 °C to reveal cyclopentanol **19** with the silylated alkynyl group intact in 96% yield.[13] After oxidation with Dess-Martin periodinane, cyclopentanone **20** was treated with LDA at −78 °C, and the corresponding lithium enolate was trapped with TMSCl. The crude enolsilane was then oxidized with 4-methoxypyridine *N*-oxide (MPO) and IBX in a mixed DMSO/DCM solvent system, to afford a mixture of enone **21** and unreacted ketone **20**.[14] The inseparable mixture of **20**/**21** was treated with divinylcuprate in THF at −78 to −30 °C to provide **22** in 49% yield, along with recovered **20** in 43% yield.[15] Removal of the protective groups of **22** was achieved sequentially, first using $BF_3{\cdot}OEt_2/Me_2S$ to deprotect the MOM group of **22** to give **23**, then using potassium carbonate/MeOH for *C*-desilylation to reveal terminal alkyne **24**.

Next, the hydroxyl group of **24** was protected as an acetate (**25**) and as a pivalate (**26**),[16] to examine the effects of these acyl groups on the oxymercurative aldol reaction, in which the hydration of the carbon−carbon triple bond proceeded spontaneously to an intramolecular aldol cyclization (Table 1). Acetate **25** reacted to generate **27** only in rather poor yields (entries 1−6, Table 1). For example, under the optimized conditions (entry 5) for the reaction of analogous substrate **11** (R= H, R′= Ac), acetate **25** was converted to **27** in just 25% yield.[17]

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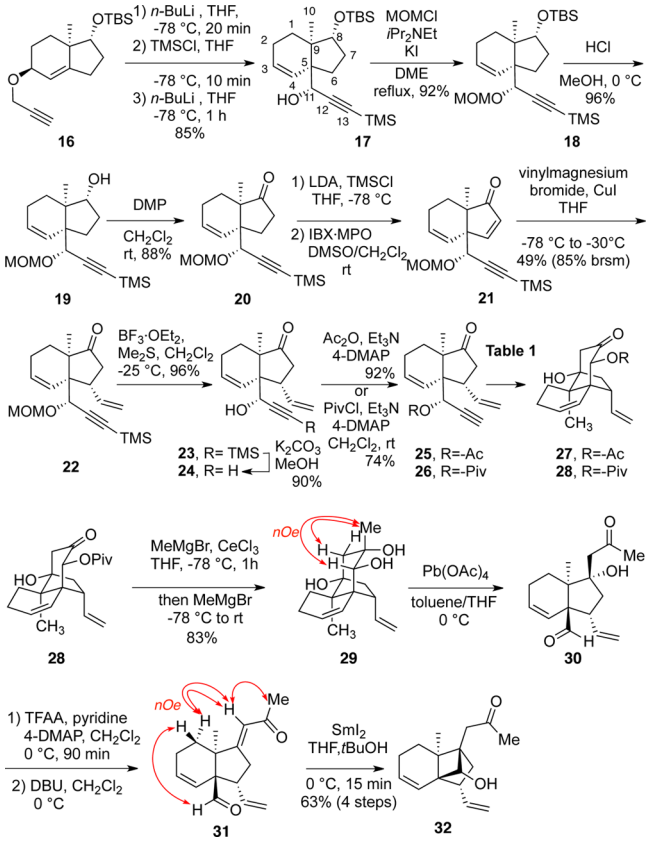
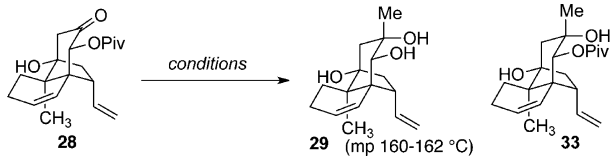
Scheme 2. Synthesis of Tricyclo[5.2.1.0^{1,6}]decene 32



We then studied the reaction of pivalate **26** with $Hg(OTFA)_2$ in mixed solvents as shown in Table 1 (entries 7–14). A comparison of the results in entries 7–14 shows that changing the temperature, ratios of acid (AcOH, TfOH, or TFA) and solvents (THF or acetone and water) could afford tricyclic product **28** in a range of yields from 22 to 70%. Among them we found the optimum conditions of conducting the reaction at −10 °C in a medium of TFA:THF:water in a ratio of 4:6.5:1 (entry 12) to provide the highest yield of **28** of 70% yield. When we applied these optimum conditions to acetate **25**, we still obtained **27** in only 23% yield (entry 15). Needless to say, this reaction did not take place under the acidic conditions in the absence of the mercury salt (entry 16).

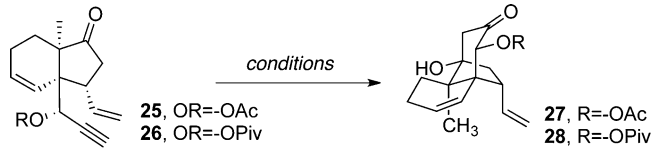
Reaction of 28 To Generate 1,2-Glycol 29 and Further Synthesis to 32. Having the best yield of 70% of pivalate **28** in hand, we progressed in our synthesis as outlined in Scheme 2 in preparation for the radical cyclization step. Now that the substrate has a pivaloyl group, it was difficult to deprotect it at this stage in the presence of the carbonyl group, and the strategy had to deviate from the previous route. To obtain a 1,2-glycol for the following oxidative C–C bond cleavage, we examined the methyl addition to ketone **28** in order to generate a new 1,2-diol **29** (Table 2). The use of MeLi alone (entry 1) afforded **29** stereoselectively (X-ray crystallographic analysis, see SI pp S64–65), but only in a moderate yield. In the presence of $CeCl_3$, diol **33** with the pivaloyl group intact was obtained in good yield (entry 3). On the contrary, treatment of

Table 2. Reaction of 28 To Generate 1,2-Glycol 29



entry	reagents	solvents	product	yield
1	**MeLi**	−78 °C to rt	**29**	54%
2	**MeMgBr**	−78 °C to rt	**29**	74%
3	**MeLi, $CeCl_3$**	−78 °C	**33**	88%
4	**MeMgBr, $CeCl_3$ then MeMgBr**	−78 °C to rt	**29**	83%
5	**$AlMe_3$**	0 °C to rt	**33**	75%

Table 1. Effects of Protective Group, Acid, and Solvent on Cyclization



entry	−OR	reagents	acid and solvents	temp	yield
1	−OAc	$Hg(OAc)_2$	$AcOH/H_2O$ (3:1)	0 to 17 °C	24%
2	−OAc	$Hg(OAc)_2$	$AcOH/THF/H_2O$ (2:2:1)	0 °C	21%
3	−OAc	$Hg(OAc)_2$	$AcOH/THF/H_2O$ (1:8:1)	−25 to 10 °C	15%
4	−OAc	$Hg(OAc)_2$	THF/H_2O (9:1)	−25 to 10 °C	19%
5	−OAc	$Hg(OAc)_2$, *p*TSA-H_2O	$TFA/THF/H_2O$ (1:7:1)	−25 °C to −10 °C	25%
6	−OAc	$Hg(OTFA)_2$	MeOH	−15 °C	0%
7	−OPiv	$Hg(OTFA)_2$, $BF_3·OEt_2$	$AcOH/THF/H_2O$ (1:6.5:1)	−10 °C	22%
8	−OPiv	$Hg(OTFA)_2$	$TfOH/THF/H_2O$ (1:6.4:2)	−10 °C	31%
9	−OPiv	$Hg(OTFA)_2$	$TfOH/THF/H_2O$ (1:6.4:2)	−20 °C	28%
10	−OPiv	$Hg(OTFA)_2$	$TFA/acetone/H_2O$ (3:6:1)	−20 °C	41%
11	−OPiv	$Hg(OTFA)_2$	$TFA/THF/H_2O$ (3:6:1)	−10 °C	64%
12	−OPiv	$Hg(OTFA)_2$	$TFA/THF/H_2O$ (4:6.5:1)	−10 °C	70%
13	−OPiv	$Hg(OTFA)_2$	$TFA/THF/H_2O$ (6:6:1)	−10 °C	43%
14	−OPiv	$Hg(OTf)_2$	THF/H_2O (20:1)	−20 °C to rt	32%
15	−OAc	$Hg(OTFA)_2$	$TFA/THF/H_2O$ (4:6.5:1)	−10 °C	23%
16	−OPiv		$TFA/THF/H_2O$ (4:6.5:1)	−10 °C	0%

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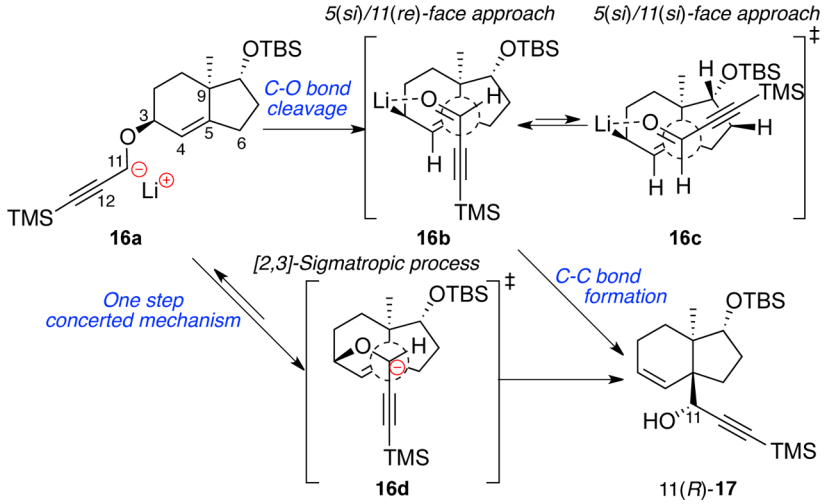
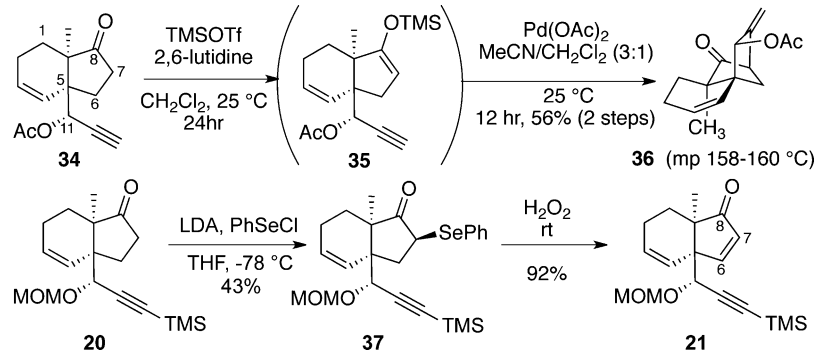
Scheme 3. Possible Mechanisms of [2,3]-Wittig Rearrangement of 16 to 17



Scheme 4. Enolization of the 8-Ketone 34 and 20 for Attempted Synthesis of Cyclopentenone 21



28 with MeMgBr, with or without $CeCl_3$ (entry 2 or 4) afforded only **29** in good yields.[18] The best conditions were treating **28** with the MeMgBr-$CeCl_3$ complex at −78 °C, then with an additional equivalent of MeMgBr at −78 °C upon full consumption of **28**. This protocol generated triol **29** in 83% yield (entry 4). Using $AlMe_3$ at 0 °C to rt, however, gave only **33** in 75% yield (entry 5).

The oxidative cleavage of the 1,2-glycol moiety of **29** was induced by treatment with $Pb(OAc)_4$ at 0 °C in a mixed solvent of toluene/THF to give aldehyde **30** (Scheme 2). Due to potential instability of the aldehyde, the subsequent three-steps were conducted directly without purification. The dehydration was carried out in two steps by first activating **30** to the corresponding trifluoroacetate, and then treatment with DBU to give the unsaturated methyl ketone **31**. Thus, the successful olefination of cyclopentanone **26** was achieved. Finally, **31** in a mixed solvent of THF:^{t}BuOH (5:1), was treated with a freshly prepared SmI_2 in THF to afford **32** in 63% yield over 4 steps from **29**. Thus, as shown in Scheme 2, the synthesis of **32** having rings DEF was achieved in 15 steps from **16** and in an overall yield of 8.6%.

DISCUSSIONS

The current synthesis in Scheme 2 features five essential steps to reach the target tricyclo[5.2.1.0^{1,6}]decene **32**: (i) [2,3]-Wittig rearrangement, (ii) introduction of 6-α−vinyl group as a masked OH, (iii) oxymercurative aldol cyclization, (iv) oxidative C−C bond cleavage of 1,2-glycol to a ketoaldehyde, and (v) radical cyclization to generate the cyclobutane ring. In this section, some of these steps are discussed.

[2,3]-Wittig Rearrangement[19] of Allyl Propargyl Ether. Recently we have published a systematic study of [2,3]-Wittig rearrangements of dihydropyran-propargyl ethers, as well as a review article.[20] In this article we reported that, in the cases where stabilization of the precursor was possible through the formation of a five membered-ring chelate of lithium coordinating with the ether oxygen atom, a higher energy to overcome the transition state of the concerted reaction was sometimes required in a cyclic system. We have proposed that, in such cases, a two-step mechanism that proceeds through a comparatively lower energy TS could predominate. In the two-step mechanism, the propargyllithium derivative first undergoes allylic C−O bond cleavage to form an allyllithium species and a propargyl aldehyde, then the allyllithium adds to the aldehyde under chelation control resulting in C−C bond formation.

In rationalizing the [2,3]-Wittig rearrangement of compound **16**, if the mechanism is a two-step process, then deprotonation generates propargyllithium **16a** that proceeds to C−O bond cleavage (Scheme 3). The resultant allyllithium-propargyl aldehyde complex could undergo C−C bond formation via two possible chelated transition states **16b** or **16c**, where **16c** should be destabilized due to steric interactions between TMS-alkynyl group and cyclopentane moiety. From **16b**, carbon−carbon bond formation occurs from the 5-(*si*)/11-(*re*) faces to provide exclusively **17** having an (*R*)-configuration at C11. Alternatively, if the rearrangement proceeds by a concerted

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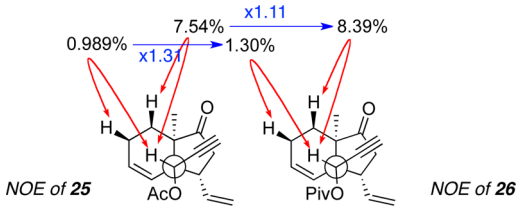
mechanism, it can be assumed that nonstereoselective deprotonation would form both C11−(*R*) and −(*S*) lithiated species **16a**, but because the C−C bond formation would be the rate-determining step, the rearrangement would afford the same product **17**. Moreover, the pseudoaxial configuration of the 3β-oxygen atom promotes the rearrangement of **16a** to give **17**. In fact, the analogous [2,3]-Wittig reaction of a Hajos-Parrish ketone derivative having the oxygen in a pseudoequatorial orientation was found to provide the rearrangement product in low yield with concomitant elimination to the corresponding diene compound.[21]

Introduction of C6-α-Vinyl Group as a Masked C6-OH Through Enone 21. We needed to prepare cyclopentenone **21** for the introduction of a vinyl group as a masked form of the C6-OH. Attempting to convert **34** into an enone under Ito-Saegusa conditions[22] afforded instead tricyclic compound **36** in 56% yield (Scheme 4). The structure of **36** was confirmed by X-ray crystallographic analysis (SI pp S66−67). Apparently, the palladium probably coordinated with the alkynyl group rather than the enolsilane to facilitate an alternative addition reaction.

We have examined another strategy to generate enone **21** without great success. Selenylation of **20** afforded only 43% of the 7-β−selenide **37**. It was oxidized with H_2O_2 and then warmed to rt to provide enone **21** in 92% yield.

Finally, the oxidation of **20** to **21** was best achieved with IBX·MPO, as shown in Scheme 2.

Scheme 5. Difference in the Dominant Conformation of 25 and 26 Analyzed from NOE Experiments

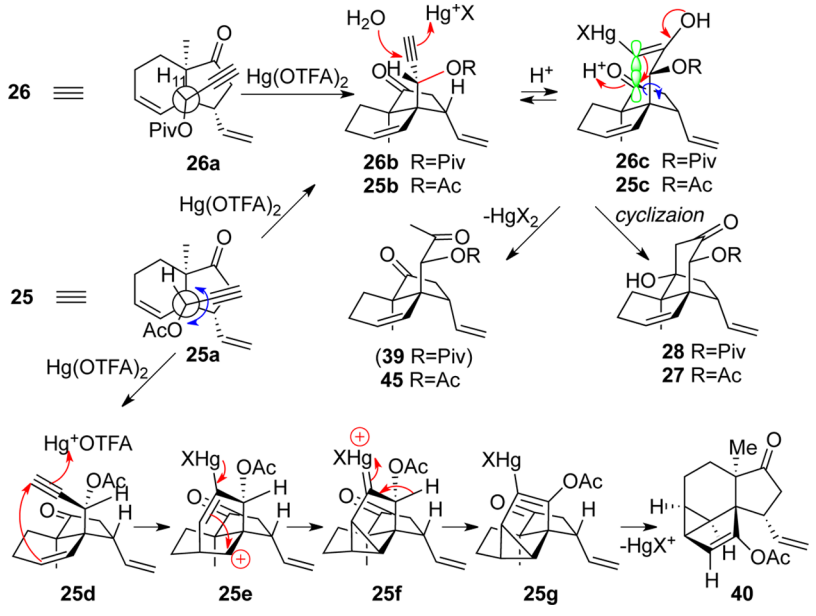


Selectivity in the Oxymercurative Cyclization of Acetate 25 and Pivalate 26. As summarized in Table 1, pivalate **26** afforded the tricyclic product **28** in higher yields than the corresponding acetate **25**. We surmised that the difference in the reaction outcomes between the pivalate and acetate (e.g., entry 12 and 15) may be due to subtle differences in the dominant conformation around C5/C11 axis (Scheme 5). While the relative NOE experimental data of both of these two compounds show strong NOE cross peaks between H1β/H2β and H11, the degree of NOE enhancement suggests different dominant rotational isomers (see Supporting Information pp S61−62).

In fact, semiquantitative measurements by means of 1D NOE of the acetate **25** and pivalate **26** recorded the differences as shown in Scheme 5. The enhancement in NOE signal between H-11 and H-2β is 1.31 times higher in **26** than **25**, while the intensity between H-11 and H-1β being only 1.11 times higher, which suggests the dihedral angles (DH) of H11−C11/C5-C6 of **26** and **25** are slightly different.

While the dihedral angles (DH) of H11−C11/C5-C6 of **26a** and **25a** seem to be only slightly different based on the NOE data, the energetic differences are further exacerbated due to the rotational barrier for pivalate **26** being higher than **25** simply due to the difference in size of both protecting groups (Scheme 6). The oxymercurated intermediate **26c** can undergo the aldol cyclization reaction producing **28** with 70% yield according to the optimized condition described under entry 12 (Table 1). Formation of methylketone **39** from **26** was found only in small amount 5−10%. The corresponding acetate **25** may go through a similar process (**25b**/**25c**) but gave low yield of **27** (Scheme 6). This could be explained by the smaller acetyl group favoring rotamer **25d** having the acetoxyl group over the cyclopentanone ring as a considerable population, so that the π-electrons of alkyne and alkene groups could overlap and favor a carbomercuration TS leading to the formation of cation **25e**. This cation cyclizes to cyclopropane **25f**, which then deprotonates (**25f**) and demercurates (**25g**) to afford vinylacetate **40**. In fact this cyclopropane side product **40** was found in small amounts only from the reaction of acetate **25** when the

Scheme 6. Plausible Mechanism of Oxymercurative Cyclization of 25 and 26 and Cycloisomerization of 25



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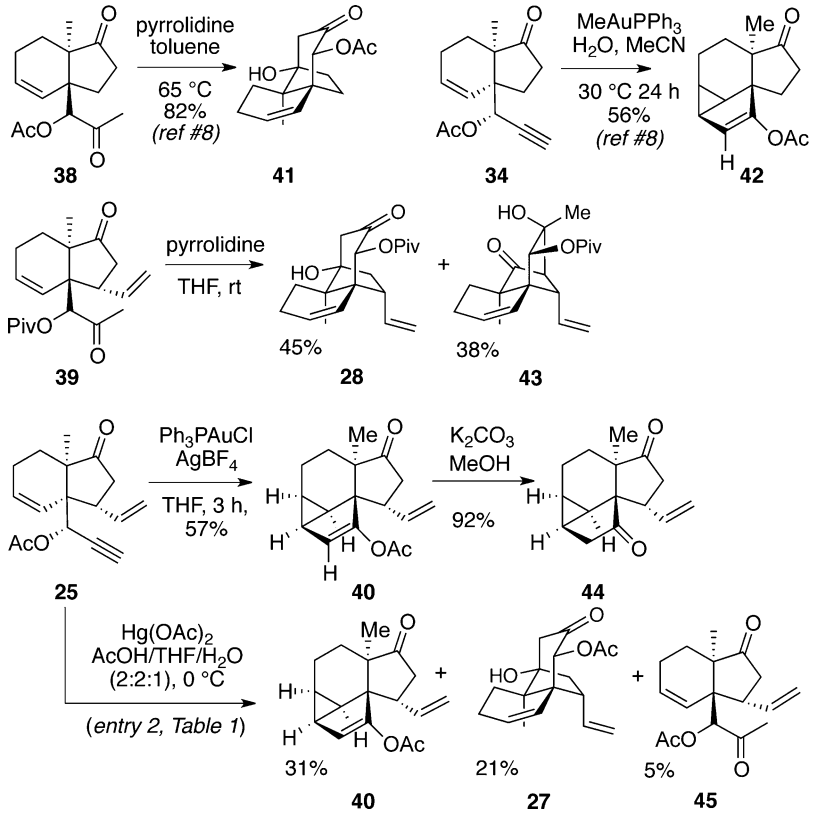
Scheme 7. Attempted Functionalization of the Alkyne or Methylketone Group



oxymercuration was conducted above −10 °C (entries 1−4 in Table 1). When the reaction temperatures were below −10 °C (entries 5−16) no cyclopropanated products were observed. Such cycloisomerization of 1,5-enyne system has been reported with gold-, platinum-, and palladium-catalysis but not with mercury.[23]

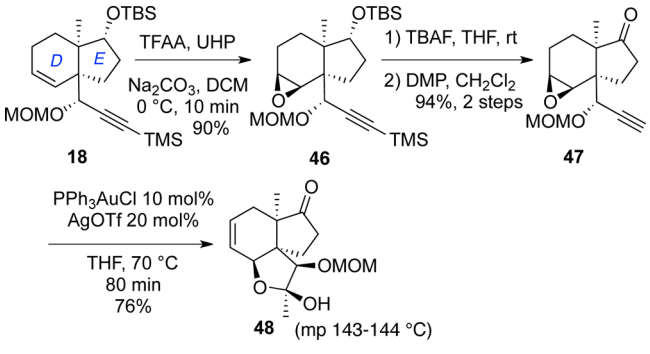
Further Functionalization. Our previous work showed that the oxymercuration of the carbon−carbon triple bond of **11** (R = H, R′=Ac) in Scheme 1, and the following aldol cyclization generated **10** (R = H, R′=Ac) in two steps. The mechanism has been confirmed to be going through the intermediate methyl ketone **38**, which could be isolated and converted to **41** by treatment with pyrrolidine in 82% yield.[8]

However, under similar reaction conditions, the corresponding pivalate **39** having the additional vinyl substituent afforded two tricyclic aldol cyclization products **28** and **43** in 45% and 38% yield, respectively (Scheme 7). We were not able to prevent the formation of undesired aldol product **43**. Such differences in the chemo-selectivity in the reactions of **38** and **39** may be due to the different acyl groups employed but more likely because of the increased steric hindrance due to the C6-vinyl group.

We have also reported a gold catalyzed reaction of **34**, which afforded the interesting cyclopropane product **42**. When we examined the gold-catalyzed reaction of acetoxyalkyne **25** which has an additional vinyl substituent compared with **34** (Scheme 7), an analogous cyclopropanated compound **40** was obtained in 57% yield. Surprisingly, cyclopropane **40** was also found as a minor product (5−15%) in the oxymercuration reactions of **25** described in entries 1−6 in Table 1, the same cyclopropane derivative **40** was isolated in 31% together with **27**, and the simple hydration product, **45** (Scheme 7). Acetate **40** was converted to **44** upon treatment with K_2CO_3 in MeOH. Such cyclopropyl ring products had never been observed in the oxymercuration reactions of the C11-*O*-pivaloyl substrate **26** (entries 7−14 in Table 1).

Attempted Cyclization by Gold-Catalysis. To modify the reactivity of the double bond in the D-ring of **18** (Scheme 8), it was first oxidized using urea-hydroperoxide (UHP)/

Scheme 8. Activation of Acetylene on the Ring Epoxide in Place of Ring Olefin



TFAA to *β*-epoxide **46** in 90% yield. Desilylation of both *C*- and *O*-silyl groups with TBAF yielded an alcohol, which was further oxidized to ketone **47**. Subjecting it to the gold catalysis[24] afforded oxytricyclic compound **48** (mp 143−144 °C). The structure of **48** was elucidated via X-ray crystallographic analysis (see SI, Figures S68−69).

A plausible reaction mechanism for the formation of **48** is proposed in Scheme 9. First, coordination of gold to the terminal alkynyl group **47a** invites the oxygen of the neighboring epoxide to attack to give **47b**. Subsequent H-2

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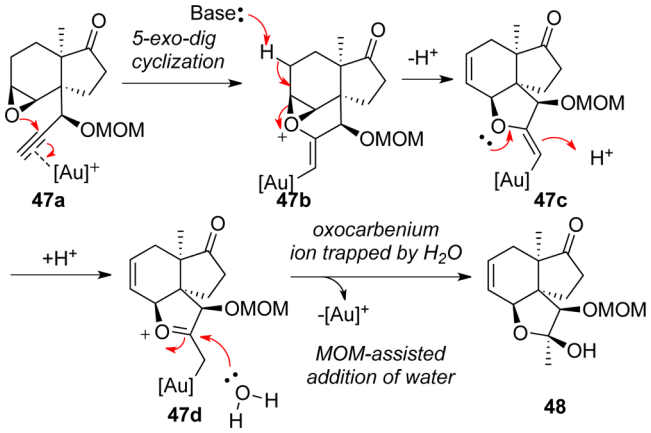
Scheme 9. Plausible Mechanisms for the Formation of 48



deprotonation generates vinyl ether **47c**. Protonation to oxocarbenium **47d**, which is trapped by a water molecule from MOM-assisted side, leads to hemiacetal formation, and finally deauration gives **48**. The structure of **48** was confirmed by X-ray crystallographic analysis (see SI pp S68–69).

Radical Cyclization. It is notable that we found an important solvent effect in the SmI_2-induced radical cyclization of **31** to **32** (Scheme 2).[25] In our previous work, we had a larger excess of samarium reagent, in fact, 9 equiv of CH_2I_2 to prepare SmI_2 in methanol to obtain a 63% yield of cyclization product. Since the solubility of SmI_2 in THF is only 0.1 M, the amount of reagent in solution must be ca. 2.9 equiv. Changing from MeOH to ^{t}BuOH as cosolvent in THF, the formation of an acetal is prevented (possible structure is assumed on SI S63).[26] When an insufficient amount of samarium reagent is present, the aldehyde reacts relatively faster than undergoing acetal formation, and afforded a 63% yield of cyclization product in a single step. When using *t*-BuOH in place of MeOH, only 2.0 equiv of SmI_2 were needed to give **32** with 63% overall yield (4 steps).

CONCLUSION AND SUMMARY

The current article has extensively discussed the synthesis of rings DEF of the target natural product solanoeclepin A (**1**), by further elaborating on our original disconnections as we reported in 2014.[8] In this case, introduction of a handle in **32** that could eventually provide the 6-OH was achieved by incorporating a vinyl group at C15 of **1**. To accommodate this, we needed to change the C11–O-protective group, and introduce the vinyl group through conjugate addition to enone **21**. Further improvement was made in the oxy-mercurative cyclization reaction to **26**, which was only successful with C11–O-pivalate and proceeded with a poor yield with the corresponding acetate **27**. The deprotection of the pivalate group in **28** was, however, not straightforward because of the presence of an additional carbonyl group. We achieved this by to detouring through a methyl adduct to **28**, which was cleaved oxidatively to afford the 1,2-diol **29** leading to unsaturated ketoaldehyde **31**. The samarium reduction was improved to require only two equivalents of SmI_2, by changing the reaction solvent from MeOH to ^{t}BuOH. The final compound **32** described in this article will be used for the further coupling with the AB rings. Further progress will be reported in due course.

EXPERIMENTAL SECTION

General Information. THF was distilled over sodium metal with benzophenone ketyl prior to use. CH_2Cl_2 was distilled from CaH_2 prior to use. Reactions were monitored by thin-layer chromatography carried out on 0.25 mm silica gel 60 F_{254} coated glass plates using UV light to visualize and/or ammonium molybdate tetrahydrate solution and heating as developing agents. Silica gel 60 (particle size 40–63 μm) was used for flash column chromatography. ^{1}H NHR spectra were recorded on a 400 or 600 MHz spectrometer. Data are reported as follows: chemical shift as δ values referenced to $CHCl_3$ (7.24 ppm), integration, multiplicity (s = singlet, d = doublet, t = triplet, q = quartet, m = multiplet, ABq = AB quartet, br = broad), coupling constants in Hz, and assignment. ^{13}C NMR spectra were recorded on a 100 or 150 MHz spectrometer. Chemical shifts are reported in δ values and referenced to $CHCl_3$ (77.00). High-resolution mass spectra (HRMS) were recorded on an ESI-TOF (electrospray ionization-time-of-flight). Infrared spectra were recorded on an FT-IR spectrometer and reported in terms of wavenumber (cm^{-1}).

*(R)-1-((1R,3aS,7aR)-1-((tert-Butyldimethylsilyl)oxy)-7a-methyl-2,3,3a,6,7,7a-hexahydro-1H-inden-3a-yl)-3-(trimethylsilyl)prop-2-yn-1-ol (**17**).* To a solution of alkyne **16** (1.1 g, 3.5 mmol) in dry THF (23 mL) at −78 °C under argon atmosphere was added *n*-butyllithium (2.08 M in hexane; 2 mL, 4.3 mmol). After stirring for 20 min at −78 °C, freshly distilled chlorotrimethylsilane (0.86 mL, 4.3 mmol) was added to this mixture, which was kept stirring for further 10 min. Then additional amount of *n*-butyllithium (2.08 M in hexane; 2 mL, 4.3 mmol) was added to this mixture, which was kept stirring at −78 °C for 1 h. The reaction was quenched with saturated aqueous NH_4Cl and extracted with EtOAc (20 mL × 3). The combined organic layer was dried over $MgSO_4$, and the solvent was removed *in vacuo*. The residue was purified by column chromatography (silica gel, EtOAc/hexane 1:100 → 1:50) to give the rearrangement product **17** (933 mg, 85%) as pale yellow oil. R_f= 0.63 (EtOAc/hexane 1:10); IRν_{max} (neat, cm^{-1}): 3587, 2171, 1250, 839, 760; ^{1}H NMR (400 MHz, $CDCl_3$): δ 0.02 (1H, 6H, s), 0.12 (9H, s), 0.85 (9H,s), 0.86 (3H, s), 1.38–1.41 (1H, m), 1.49–1.58 (1H, m), 1.72–1.80 (1H, m), 1.91–1.97 (1H, m), 2.04–2.13 (4H, m), 4.08 (1H, dd, J = 8.7, 6.2 Hz), 4.27 (1H, d, J = 10.2 Hz), 5.73 (1H, d, J = 9.9 Hz), 5.93 (1H, dt, J = 9.9, 2.9 Hz); ^{13}C NMR (100 MHz, $CDCl_3$): δ −4.9 (CH_3), −4.6 (CH_3), −0.2 (CH_3 × 3), 18.0 (C), 18.8 (CH_3), 24.1 (CH_2), 25.8 (CH_3 × 3), 28.2 (CH_2), 28.6 (CH_2), 30.6 (CH_2), 46.6 (C), 52.7 (C), 66.3 (CH), 76.9 (CH), 89.1 (C), 106.8 (C), 127.9 (CH), 132.0 (CH); HRMS (ESI): calcd for $[C_{22}H_{40}O_2Si_2+H]^+$ 393.2639; found 393.2637: $[\alpha]^{25}_D$ + 31.4 (*c* 4.1, $CHCl_3$).

*tert-Butyl(((1R,3aS,7aR)-3a-((R)-1-(methoxymethoxy)-3-(trimethylsilyl)prop-2-yn-1-yl)-7a-methyl-2,3,3a,6,7,7a-hexahydro-1H-inden-1-yl)oxy)dimethylsilane (**18**).* A solution of alcohol **17** (7 g, 18 mmol) was dissolved in dimethoxymethane (130 mL) at room temperature, to which were added *N*,*N*-diisopropylethylamine (31 mL, 180 mmol), chloromethyl methyl ether (ca. 2.1 M in dichloromethane, 51 mL, 108 mmol), and potassium iodide (14.9 g, 90 mmol). The resulting mixture was stirred at room temperature for 30 min and then heated at 85 °C for 24 h. After TLC analysis showed consumption of the starting material, the reaction was cooled to room temperature and poured into saturated $NaHCO_3$. The aqueous layer was separated and extracted with EtOAc (50 mL

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× 3). The combined organic layer was washed with brine and dried over $MgSO_4$. The solution was concentrated to dryness *in vacuo*. The residue was purified by column chromatography (silica gel, EtOAc/hexane 1:100) to give compound **18** (7.2 g, 92%) as pale yellow oil. R_f= 0.8 (EtOAc/hexane 1:10); IR ν_{max} (neat, cm^{-1}): 2165, 1617, 1019, 840; ^1H NMR (400 MHz, $CDCl_3$): δ 0.01(9H, s), 0.14 (12H, s), 0.86 (9H, s), 0.89 (3H, s), 1.47 (1H, dd, J = 12.6, 7.4 Hz), 1.54−1.60 (1H, s), 1.68 (1H, td, J = 12.6, 6.2 Hz), 1.89−1.99 (2H, m), 2.09−2.19 (3H, m), 3.35 (3H, s), 4.27 (1H, s), 4.46 (1H, d, J = 6.4 Hz), 4.47 (1H, ABq, d, J = 6.8 Hz), 4.95 (1H, ABq, d, J = 6.8 Hz), 5.62 (1H, dt, J = 9.9, 3.4 Hz), 5.79 (1H, ddd, J = 9.9, 2.1, 1.9 Hz); ^{13}C NMR (100 MHz, $CDCl_3$): δ −4.8 (CH_3), −4.3 (CH_3), −0.1 (CH_3 × 3), 18.0 (CH_3 and C), 23.1 (CH_2), 25.8 (CH_3 × 3), 27.6 (CH_2), 27.7 (CH_2), 31.7 (CH_2), 47.2 (C), 52.2 (C), 56.3 (CH_3), 71.8 (CH), 76.9 (CH), 91.5 (C), 93.9 (CH_2), 104.2 (C), 127.9 (CH), 131.3 (CH); HRMS (ESI): calcd for $[C_{24}H_{44}O_3Si_2+Na]^+$ 459.2721; found 459.2720: $[\alpha]^{25}_D$ + 108.6 (*c* 2.5, $CHCl_3$).

*(1R,3aS,7aR)-3a-((R)-1-(Methoxymethoxy)-3-(trimethylsilyl)prop-2-yn-1-yl)-7a-methyl-2,3,3a,6,7,7a-hexahydro-1H-inden-1-ol (**19**).* To a solution of silyl ether **18** (7 g, 16 mmol) in methanol (160 mL) at 0 °C was added HCl (5% in methanol, 28 mL), and the reaction was stirred at 0 °C for 12 h. The reaction mixture was neutralized with saturated $NaHCO_3$ to pH 8 and the methanol was removed under reduced pressure. The residual aqueous layer was extracted with EtOAc (100 mL × 3). The combined organic layer was dried over $MgSO_4$ and the solution was concentrated to dryness *in vacuo*. The residue was purified by column chromatography (silica gel, EtOAc/hexane 1:15 → 1:10) to give alcohol **19** (5.1 g, 96%) as colorless oil. R_f= 0.44 (EtOAc/hexane 1:4); IRν_{max} (neat, cm^{-1}): 3101, 2167, 1250, 1636, 1021, 843; ^1H NMR (400 MHz, $CDCl_3$): δ 0.13 (9H, s), 0.92 (3H, s), 1.49−1.58 (2H, m), 1.67 (1H, td, J = 12.0, 6.4 Hz), 1.93 (1H, ddd, J = 12.8, 9.7, 2.8 Hz), 2.03−2.22 (3H, m), 2.31 (1H, m), 3.33 (3H, s), 4.24 (1H, s), 4.47 (1H, ABq, d, J = 6.8 Hz), 4.52 (1H, dd, J = 9.0, 7.0 Hz), 4.92 (1H, ABq, d, J = 6.8 Hz), 5.63 (1H, dt, J = 9.7, 2.9 Hz), 5.79 (1H, d, J = 9.9 Hz); ^{13}C NMR (100 MHz, $CDCl_3$): δ 0.33 (CH_3 × 3), 17.7 (CH_3), 23.5 (CH_2), 27.4 (CH_2), 27.6 (CH_2), 31.4 (CH_2), 46.9 (C), 52.6 (C), 56.4 (CH_3), 71.7 (CH), 76.9 (CH), 91.6 (C), 94.0 (CH_2), 103.9 (C), 128.1 (CH), 130.8 (CH); HRMS (ESI): calcd for $[C_{18}H_{30}O_3Si+Na]^+$ 345.1856; found 345.1856: $[\alpha]^{25}_D$ + 110.2 (*c* 9.9, $CHCl_3$).

*(3aS,7aR)-3a-((R)-1-(Methoxymethoxy)-3-(trimethylsilyl)-prop-2-yn-1-yl)-7a-methyl-2,3,3a,6,7,7a-hexahydro-1H-inden-1-one (**20**).* To a solution of alcohol **19** (4.9 g, 15.3 mmol) in dichloromethane (77 mL) at 0 °C was added Dess-Martin periodinane (11.7 g, 27.5 mmol), and the reaction was gradually allowed to warm to room temperature for 4 h. After TLC analysis indicating no more starting material, the reaction was poured into saturated $NaHCO_3$ to destroy unreacted Dess-Martin periodinane. The aqueous layer was separated and extracted with dichloromethane (50 mL × 3). The combined organic layer was washed with brine, dried over $MgSO_4$, and the solution was concentrated to dryness *in vacuo*. The residue was purified by column chromatography (silica gel, EtOAc/hexane 1:20 → 1:15) to give ketone **20** (4.3 g 88%) as colorless oil. R_f= 0.69 (EtOAc/hexane 1:4); IRν_{max} (neat, cm^{-1}): 2955, 2891, 2170, 1741,1250, 1153, 1071, 1020, 884; ^1H NMR (400 MHz, $CDCl_3$): δ 0.09 (9H, s), 0.97 (3H, s), 1.64 (1H, dd, J = 13.8, 8.4 Hz), 1.75−1.84 (1H, m), 1.89 (1H, dt, J = 13.8, 8.8 Hz), 2.06−2.26 (1H, m), 2.34−2.43 (1H, m), 2.56 (1H, ddd, J = 17.5, 9.1, 7.6 Hz), 4.17 (1H, s), 4.46 (1H, ABq, d, J = 6.8 Hz), 4.89 (1H, ABq, J = 6.8 Hz), 5.56 (1H, dt, J = 9.6, 3.4 Hz), 5.85 (1H, dt, J = 9.6, 2.3 Hz); ^{13}C NMR (100 MHz, $CDCl_3$): δ 0.81 (CH_3 × 3), 21.7 (CH_3), 22.9 (CH_2 × 2),23.4 (CH_2), 35.1 (CH_2), 50.5 (C), 51.7 (C), 55.8 (CH_3), 72.9 (CH), 93.6 (CH_2), 95.7 (C), 101.4 (C), 127.5 (CH), 132.5 (CH), 217.2 (C); HRMS (ESI): calcd for $[C_{18}H_{28}O_3Si+Na]^+$ 343.1700; found 343.1698: $[\alpha]^{25}_D$ + 94.4 (*c* 2.2, $CHCl_3$).

*(3R,3aR,7aR)-3a-((R)-1-(Methoxymethoxy)-3-(trimethylsilyl)prop-2-yn-1-yl)-7a-methyl-3-vinyl-2,3,3a,6,7,7a-hexahydro-1H-inden-1-one (**22**). Preparation of 1 M LDA in THF (10 mL).* To a solution of diisopropylamine (1.4 mL, 10 mmol, freshly distilled from calcium hydride) in THF (4.4 mL, freshly distilled from sodium/benzophenone) at 0 °C under argon was added *n*-butyllithium (2.38 M in hexane, 4.2 mL, 10 mmol) dropwise with stirring at 0 °C for 10 min.

This solution of LDA (1 M in THF, 7.3 mL, 7.3 mmol) was added dropwise to a solution of ketone **20** (1.55 g, 4.84 mol) in THF (33 mL) under argon atmosphere at −78 °C. After stirring for 10 min at this temperature, a freshly distilled chlorotrimethylsilane (0.92 mL, 7.27 mmol) was added to the enolate solution at −78 °C and the mixture was stirred for 10 min. After TLC analysis indicated that all the ketone was converted to vinyl silyl ether, the reaction was poured into an ice-cold saturated NH_4Cl (20 mL). The aqueous mixture was extracted with EtOAc (20 mL × 3). The combined organic layer was washed with brine, dried over $MgSO_4$, and the solution was concentrated to dryness *in vacuo* to give crude vinyl silyl ether. In another reaction vessel was placed a solution of IBX (2 g, 7.26 mmol) in dimethyl sulfoxide (18 mL), to which was added 4-methoxypyridine *N*-oxide (908 mg, 7.26 mmol). After stirring for 30 min at room temperature, a solution of the crude vinyl silyl ether dissolved in dichloromethane (9 mL) was added to the solution of IBX/4-methoxylpyridine *N*-oxide at room temperature. The resulting mixture was stirred at room temperature for 18 h. After TLC analysis that all the vinyl silyl ether was consumed, the reaction mixture was diluted with diethyl ether (18 mL) and saturated $NaHCO_3$ (18 mL) by dropwise addition to quench the reaction. The aqueous layer was separated and extracted with diethyl ether (18 mL × 3). The combined organic layer was washed with brine, dried over $MgSO_4$, and the solution was concentrated to dryness *in vacuo*. The residue was purified by passing through a short column of silica gel (EtOAc/hexane 1:20) to afford a mixture of ketone **20** and enone **21** (1.38 g) as yellow oil.

Vinylmagnesium bromide (0.7 M in THF, 12.3 mL, 8.6 mmol) was added to a stirred suspension of CuI (821 mg, 4.3 mmol) in THF (11 mL, freshly distilled from sodium/benzophenone) at −78 °C. The resulting yellow solution was stirred for 30 min at −78 °C, and then a solution of ketone **20** and enone **21** (1.38 g) in THF (16 mL) was added dropwise to the cuprate solution via cannula. The reaction mixture was stirred at −78 °C for 30 min and warmed to −30 °C. After 1 h stirring at −30 °C, the mixture was poured into an ice-cold saturated NH_4Cl (15 mL) solution. The aqueous layer was separated and extracted with EtOAc (15 mL × 3). The combined organic layer was washed with brine, dried over $MgSO_4$, and the solvent was removed under reduced pressure. The residue was purified by column chromatography (silica gel, EtOAc/hexane 1:200) to give vinyl-ketone **22** (754 mg, 49%) and ketone **20** (667 mg, 43%) both as colorless oil. Vinyl-

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ketone **22**: R_f= 0.47 (EtOAc/hexane 1:10); IRν_{max} (neat, cm^{-1}): 2956, 2171, 1745, 1617, 1541, 1250, 1024, 884; ^1H NMR (400 MHz, $CDCl_3$): δ 0.14 (9H, s), 1.04 (3H, s), 1.64 (1H, dt, J = 14.0, 7.8 Hz), 1.88 (1H, dt, J = 14.0, 8.8 Hz), 2.10−2.29 (2H, m), 2.52 (1H, dd, J = 19.0, 3.9 Hz), 2.82 (1H, dd, J = 19.0, 10.1 Hz), 3.30 (3H, s), 3.37−3.43 (1H, m), 4.19 (1H, s), 4.50 (1H, ABq, d, J = 6.8 Hz), 4.90 (1H, ABq, d, J = 6.8 Hz), 5.09 (1H, dt, J = 10.2, 1.5 Hz), 5.13 (1H, dt, J = 17.0, 1.5 Hz), 5.61 (1H, dt, J = 9.8, 3.6 Hz), 5.96 (1H, ddd, J = 17.0, 10.2, 7.6 Hz), 6.01 (1H, dt, J = 2.4, 9.8 Hz); ^{13}C NMR (100 MHz, $CDCl_3$): δ 0.72 (CH_3 × 3), 22.7 (CH_2), 23.2 (CH_3), 23.8 (CH_2), 38.8 (CH), 42.3 (CH_2), 51.6 (C), 53.4 (C), 55.9 (CH_3), 74.4 (CH), 93.7 (CH_2), 96.1 (C), 101.2 (C), 115.8 (CH_2), 127.5 (CH), 130.9 (CH), 141.0 (CH), 216.6 (C); HRMS (ESI): calcd for $[C_{20}H_{30}O_3Si+Na]^+$ 369.1856; found 369.1854: $[\alpha]^{25}_D$ + 151.5 (c 1.9, $CHCl_3$). (The data of enone **21** is reported later from selenide **37**.)

*(3R,3aR,7aR)-3a-((R)-1-Hydroxy-3-(trimethylsilyl)prop-2-yn-1-yl)-7a-methyl-3-vinyl-2,3,3a,6,7,7a-hexahydro-1H-inden-1-one (**23**).* Methoxy methyl ether **22** (199 mg, 0.58 mmol) was dissolved in a mixed solvents of dichloromethane (8.2 mL) and dimethyl sulfide (2.7 mL). This solution was cooled to −25 °C, to which was added boron trifluoride diethyl etherate (0.58 mL, 4.6 mmol) under argon atmosphere. The reaction mixture was stirred at −25 °C for 22 h and then was poured into an ice-bath containing saturated $NaHCO_3$ (15 mL). The aqueous layer was separated and extracted with dichloromethane (15 mL × 3). The combined organic layer was washed with brine, dried over $MgSO_4$ and then concentrated to dryness *in vacuo*. The residue was purified by column chromatography (silica gel, EtOAc/hexane 1:15) to give alcohol **23** (168 mg, 96%) as white solid. R_f= 0.50 (EtOAc/hexane 1:4); IRν_{max} (neat, cm^{-1}): 3391, 2956, 1733, 1251, 1045, 845; ^1H NMR (400 MHz, $CDCl_3$): δ 0.13 (9H, s), 1.03 (3H, s), 1.57 (1H, dd, J = 13.8, 8.5 Hz), 1.89−1.97 (1H, m), 2.11−2.22 (2H, m), 2.53 (1H, dd, J = 19.1, 3.2 Hz), 2.76 (1H, dd, J = 19.1, 10.0 Hz), 3.40 (1H, m), 4.24 (1H, s), 5.09 (1H, d, J = 10.3 Hz), 5.14 (1H, d, J = 17.1 Hz), 5.74 (1H, m), 5.94 (1H, ddd, J = 17.1, 10.3, 7.6 Hz) 5.96−6.99 (1H, m); ^{13}C NMR (100 MHz, $CDCl_3$): δ 0.67 (CH_3 × 3), 23.0 (CH_2), 23.4 (CH_3), 23.8 (CH_2), 38.8 (CH), 42.0 (CH_2), 51.7 (C), 54.2 (C), 70.9 (CH), 94.5 (C), 103.6 (C), 116.1 (CH_2), 129.0 (CH), 129.8 (CH), 140.8 (CH), 216.7 (C); HRMS (ESI): calcd for $[C_{18}H_{26}O_2Si+H]^+$ 303.1780; found 303.1776: $[\alpha]^{25}_D$ + 14.5 (c 4.3, $CHCl_3$).

*(3R,3aR,7aR)-3a-((S)-1-Hydroxyprop-2-yn-1-yl)-7a-methyl-3-vinyl-2,3,3a,6,7,7a-hexahydro-1H-inden-1-one (**24**).* To a solution of compound **23** (134 mg, 0.44 mmol) in methanol (1.5 mL) was added potassium carbonate (121 mg, 0.88 mmol) at room temperature. This solution was stirred for 4 h at room temperature. After TLC analysis that indicated all the starting material was consumed, the reaction mixture was diluted with EtOAc (2 mL) and then with saturated NH_4Cl (2 mL). The aqueous layer was extracted with EtOAc (2 mL × 3) and the combined organic layer was washed with brine, dried over $MgSO_4$. The solution was concentrated to dryness *in vacuo*. The residue was purified by column chromatography (silica gel, EtOAc/hexane 1:15) to give compound **24** (91 mg, 90%) as colorless oil. R_f = 0.48 (EtOAc/hexane 1:2); IRν_{max} (neat, cm^{-1}): 2171, 1733, 1717, 1521, 1209, 842; ^1H NMR (400 MHz, $CDCl_3$): δ 1.07 (3H, s), 1.59 (1H, dd, J = 14.8, 8.1 Hz), 2.00−2.08 (1H, m), 2.12−2.21 (1H, m), 2.21−2.30 (1H, m) 2.55 (1H, d, J = 2.3 Hz), 2.57 (1H, dd, J = 18.3, 3.8 Hz), 2.78 (1H, dd, J = 18.3, 9.6 Hz), 3.35 (1H, m), 4.19 (1H, br s), 4.30 (1H, d, J = 2.3 Hz), 5.11 (1H, dt, J = 10.2, 1.4 Hz), 5.14 (1H, dt, J = 17.4, 1.4 Hz), 5.82 (1H, dt, J = 9.8, 3.8 Hz), 5.92−5.95 (1H, m) 5.96 (1H, ddd, J = 17.4, 10.2, 7.4 Hz); ^{13}C NMR (100 MHz, $CDCl_3$): δ 23.0 (CH_2), 23.2 (CH_3), 23.7 (CH_2), 38.8 (CH), 42.0 (CH_2), 51.8 (C), 53.9 (C), 70.1 (CH), 77.4 (CH), 82.3 (C), 116.2 (CH_2), 128.6 (CH), 130.1 (CH), 140.5 (CH), 217.6 (C); HRMS (ESI): calcd for $[C_{15}H_{18}O_2+Na]^+$ 253.1199; found 253.1201: $[\alpha]^{25}_D$ + 48.4 (c 0.9, $CHCl_3$).

*(S)-1-((3R,3aR,7aR)-7a-Methyl-1-oxo-3-vinyl-2,3,3a,6,7,7a-hexahydro-1H-inden-3a-yl)prop-2-yn-1-yl acetate (**25**).* To a solution of alcohol **24** (272 mg, 1.18 mmol) in dichloromethane (12 mL) at room temperature were added triemthylamine (0.66 mL, 4.72 mmol), 4-dimethylaminopyridine (14 mg, 0.12 mmol), and acetic anhydride (0.22 mL, 2.36 mmol). After the reaction was stirred at room temperature for 12 h, saturated $NaHCO_3$ (6 mL) was poured into the reaction mixture. The aqueous layer was extracted with dichloromethane (6 mL × 3), washed with brine and dried over $MgSO_4$. The solution was concentrated to dryness *in vacuo*. The residue was purified by column chromatography (silica gel, EtOAc/hexane 1:6) to afford acetate **25** (295 mg, 92%) as colorless oil. R_f = 0.53 (EtOAc/hexane 1:2); IRν_{max} (neat, cm^{-1}): 3013, 2118, 1743, 1541, 1227, 1019, 911; ^1H NMR (400 MHz, $CDCl_3$): δ 1.02 (3H, s), 1.63 (1H, dd, J = 8.8, 1.4 Hz), 1.88 (1H, dt, J = 8.8, 1.4 Hz), 2.01 (3H, s), 2.07−2.18 (1H, m), 2.23−2.31 (1H, m), 2.49 (1H,d, J = 2.4 Hz), 2.53 (1H, d, J = 19.1, 4.0 Hz), 2.81 (1H, dd, J = 19.1, 10.1 Hz), 3.34−3.37 (1H, m), 5.09 (1H, dt, J = 10.1, 1.5 Hz), 5.12 (1H, dt, J = 16.9,1.5 Hz), 5.20 (1H, d, J = 2.3 Hz), 5.59 (1H, dt, J = 9.8, 3.1 Hz), 5.79 (1H, dt, J = 9.8, 2.4 Hz), 5.90 (1H, ddd, J = 16.9, 10.1, 7.8 Hz); ^{13}C NMR (100 MHz, $CDCl_3$): δ 20.7 (CH_3), 22.9 (CH_2), 23.1 (CH_3), 23.5 (CH_2), 39.3 (CH), 42.1 (CH_2), 51.4 (C), 52.3 (C), 71.4 (CH), 77.9 (CH), 78.8 (C), 116.4 (CH_2), 128.3 (CH), 129.4 (CH), 140.1 (CH), 169.1(C), 216.5 (C); HRMS (ESI): calcd for $[C_{17}H_{20}O_3+Na]^+$ 295.1310, found 295.1308. $[\alpha]^{25}_D$ + 74.7 (c 1.7, $CHCl_3$).

*(1S,4R,4aR,8aR,9R)-1-Hydroxy-8a-methyl-3-oxo-9-vinyl-2,3,4,7,8,8a-hexahydro-1H-4a,1-ethanonaphthalen-4-yl acetate (**27**).* A solution of alkyne **25** (33 mg, 0.12 mmol) in THF (1.1 mL) and water (0.18 mL) was mixed at −10 °C with trifluoroacetic acid (0.73 mL). Mercury trifluoroacetate (26 mg, 0.06 mmol) was added to the alkyne solution at −10 °C and stirred for 12 h at the same temperature. Additional portion of mercury trifluoroacetate was added (26 mg, 0.06 mmol) at −10 °C and the reaction was stirred for 24 h at this temperature. The reaction was carefully added to a solution of saturated $NaHCO_3$ (1 mL) and EtOAc (1 mL) at 0 °C. The aqueous layer was extracted with EtOAc (1 mL × 3) and washed with brine, dried over $MgSO_4$. The solution was concentrated to dryness *in vacuo* and the residue was purified by column chromatography (silica gel, EtOAc/hexane 1:20 → 1:3) to give tricyclic compound **27** (8 mg, 23%) as colorless oil. R_f= 0.43 (EtOAc/hexane 1:1); IRν_{max} (neat, cm^{-1}): 3013, 2065, 1733, 1717, 1576, 1059, 918; ^1H NMR (400 MHz, $CDCl_3$): δ 1.16 (3H, s), 1.56−1.62 (1H, m), 1.98 (1H, ddd, J = 13.8, 6.2, 3.3 Hz), 2.07 (1H, dd, J = 13.8, 9.4 Hz), 2.13 (3H, s), 2.18−2.20 (1H, m), 2.25−2.41 (2H, m), 2.54 (1H, d, J = 14.8 Hz), 2.67 (1H, dd, J = 15.6, 7.7 Hz), 2.97 (1H, dd, J = 14.8, 3.1 Hz), 5.00 (1H, dt, J = 16.4, 1.4 Hz), 5.06 (1H, dt, J = 10.5, 1.4 Hz), 5.20 (1H, s), 5.64 (1H, dt, J = 10.0, 3.4 Hz), 5.70 (1H, dt, J = 10.0, 2.0 Hz), 5.81 (1H, ddd, J = 16.4, 10.5, 8.0 Hz); ^{13}C NMR (100 MHz, $CDCl_3$): δ 18.2 (CH_3), 20.6 (CH_3), 22.7 (CH_2), 24.6

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(CH_2), 40.9 (CH), 44.1 (CH_2), 47.3 (C), 50.4 (CH_2), 51.6 (C), 80.3 (C), 84.8 (CH), 116.2 (CH_2), 128.0 (CH × 2), 140.5 (CH), 170.2 (C), 200.3 (C); HRMS (ESI): calcd for $[C_{17}H_{22}O_4+H]^+$ 291.1596, found 291.1601. $[\alpha]^{25}_D$ + 26.4 (*c* 0.7, $CHCl_3$).

*(S)-1-((3R,3aR,7aR)-7a-Methyl-1-oxo-3-vinyl-2,3,3a,6,7,7a-hexahydro-1H-inden-3a-yl)prop-2-yn-1-yl pivalate (**26**).* To the solution of alcohol **24** (617 mg, 2.7 mmol) in dichloromethane (13 mL) were added triethylamine (2.2 mL, 16 mmol), pivaloyl chloride (0.69 mL, 5.4 mmol) and 4-dimethylaminopyridine (32 mg, 0.27 mmol) at room temperature. The reaction mixture was stirred at room temperature for 12 h and quenched with saturated $NaHCO_3$. The aqueous layer was extracted with dichloromethane (10 mL) and washed with brine, dried over $MgSO_4$. The solution was concentrated to dryness *in vacuo* and the residue was purified by column chromatography (silica gel, EtOAc/hexane 1:20) to give pivalate **26** (842 mg, 74%) as colorless oil; R_f= 0.71 (EtOAc/hexane 1:2); IRν_{max} (neat, cm^{-1}): 3080, 2065, 1741, 1716, 1139; ^{1}H NMR (400 MHz, $CDCl_3$): δ 1.07 (3H, s), 1.18 (9H, s), 1.67 (1H, dd, *J* = 14.1, 8.8 Hz), 1.88 (1H, dt, *J* = 14.1, 8.8 Hz), 2.10−2.21 (2H, m), 2.29 (1H, dt, *J* = 6.0, 3.4 Hz), 2.43 (1H, d, *J* = 2.1 Hz), 2.55 (1H, dd, *J* = 19.1, 4.1 Hz), 2.86 (1H, dd, *J* = 19.1, 10.0 Hz), 3.41 (1H, ddd, *J* = 9.8, 4.0, 3.0 Hz), 5.12 (1H, d, *J* = 10.0 Hz), 5.15 (1H, d, *J* = 16.8 Hz), 5.19 (1H, d, *J* = 2.1 Hz), 5.60 (1H, dt, *J* = 9.8, 3.6 Hz), 5.80 (1H, dt, *J* = 9.8, 3.6 Hz), 5.90 (1H, ddd, *J* = 16.8, 10.0, 8.5 Hz); ^{13}C NMR (100 MHz, $CDCl_3$): δ 22.5 (CH_2), 23.2 (CH_3), 23.6 (CH_2), 26.9 (CH_3 × 3), 38.8 (C), 39.8 (CH), 42.3 (CH_2), 51.5 (C), 52.6 (C), 71.4 (CH), 77.8(CH), 78.8 (C), 116.8 (CH_2), 128.6 (CH), 129.2 (CH), 140.2 (CH), 176.4 (C), 216.7 (C); HRMS (ESI): calcd for $[C_{20}H_{26}O_3+H]^+$ 315.1954, found 315.1952: $[\alpha]^{25}_D$ + 81.3 (*c* 3.4, $CHCl_3$).

*(1S,4R,4aR,8aR,9R)-1-Hydroxy-8a-methyl-3-oxo-9-vinyl-2,3,4,7,8,8a-hexahydro-1H-4a,1-ethanonaphthalen-4-yl pivalate (**28**). Experiments for Entry 12 of Table 1 as a Representative Example.* A solution of alkyne **26** (420 mg, 1.34 mmol) in THF (12 mL) and water (2 mL) was mixed at −10 °C with trifluoroacetic acid (8 mL). Mercury trifluoroacetate (286 mg, 0.67 mmol) was added to this alkyne solution at −10 °C and stirred for 12 h at the same temperature. Additional portion of mercury trifluoroacetate was added (286 mg, 0.67 mmol) at −10 °C and the reaction was stirred for 24 h at this temperature. The reaction was carefully added to a solution of saturated $NaHCO_3$ (30 mL) and EtOAc (30 mL) at 0 °C. The aqueous layer was extracted with EtOAc (30 mL × 3) and washed with brine, dried over $MgSO_4$. The solution was concentrated to dryness *in vacuo* and the residue was purified by column chromatography (silica gel, EtOAc/hexane 1:20 → 1:3) to give tricyclic compound **28** (311 mg, 70%) and methyl ketone **39** (53 mg, 12%) as colorless oil. Tricyclic compound **28**: R_f = 0.32 (EtOAc/hexane 1:2): IRν_{max} (neat, cm^{-1}): 3640, 1733, 1716, 1521, 1058; ^{1}H NMR (400 MHz, $CDCl_3$): δ 1.16 (3H, s), 1.23 (9H, s), 1.55−1.62 (1H, m), 1.97 (1H, ddd, *J* = 13.9, 6.3, 3.2 Hz), 2.07 (1H, dd, *J* = 13.9, 9.4 Hz), 2.15−2.29 (1H, m), 2.32−2.40 (1H, m), 2.52 (1H, d, *J* = 14.8 Hz), 2.68 (1H, dd, *J* = 15.4, 8.6 Hz), 2.97 (1H, dd, *J* = 14.8, 2.8 Hz), 4.96−5.02 (2H, m), 5.15 (1H, s), 5.61 (dt, *J* = 10.0, 2.8 Hz), 5.66 (1H, d, *J* = 10.0 Hz), 5.77 (1H, ddd, *J* = 18.6, 10.1, 8.6 Hz); ^{13}C NMR (100 MHz, $CDCl_3$): δ 18.2 (CH_3), 22.7 (CH_2), 24.6 (CH_2), 27.1 (CH_3 × 3), 38.9 (C), 41.5 (CH), 43.9 (CH_2), 47.2 (C), 50.5 (CH_2), 51.9 (C), 80.3 (C), 84.3 (CH), 116.4 (CH_2), 127.8 (CH), 128.0 (CH), 140.5 (CH), 177.4 (C), 200.4 (C); HRMS (ESI): calcd for $[C_{20}H_{28}O_4+H]^+$ 333.2060, found 333.2061: $[\alpha]^{25}_D$ + 2.56° (*c* 11.0, $CHCl_3$). Methyl ketone **39**: R_f= 0.63 (EtOAc/hexane 1:2); IRν_{max} (neat, cm^{-1}): 2971, 2928, 1736, 1458, 1210, 1139, 1019, 918; ^{1}H NMR (400 MHz, $CDCl_3$): δ 1.10 (3H, s), 1.20 (9H, s), 1.71 (1H, dd, *J* = 12.6, 10.6 Hz), 2.16 (s, 3H), 2.20−2.30 (2H, m), 2.35 (1H, dd, *J* = 19.5, 9.8 Hz), 2.51 (1H, dd, *J* = 19.5, 3.4 Hz), 3.32 (1H, m), 4.95(1H, s), 5.13 (1H, m), 5.16 (1H, m), 5.67 (1H, dt, *J* = 9.8, 3.2 Hz), 5.89 (1H, dt, *J* = 9.8, 2.2 Hz), 5.94 (1H, ddd, *J* = 17.6, 10.1, 7.8 Hz); ^{13}C NMR (150 MHz, $CDCl_3$): δ 23.0 (CH_2), 23.3(CH_3), 24.4 (CH_2), 26.9 (CH_3 × 3), 30.3 (CH_3), 38.7 (C), 40.7 (CH), 41.3 (CH_2), 51.8 (C), 53.2 (C), 85.4 (CH), 116.9 (CH_2), 128.3 (CH), 129.5 (CH), 139.9 (CH), 177.8 (C), 205.8 (C), 215.6 (C); HRMS (ESI): calcd for $[C_{20}H_{28}O_4+H]^+$ 333.2060, found 333.2059: $[\alpha]^{25}_D$ − 11.4 (*c* 0.5, $CHCl_3$).

*(1S,3S,4R,4aR,8aR,9R)-3,8a-Dimethyl-9-vinyl-2,3,4,7,8,8a-hexahydro-1H-4a,1-ethanonaphthalene-1,3,4-triol (**29**).* Anhydrous cerium chloride (2.5 g, 10.3 mmol, cerium chloride being heated at 120 °C under vacuum for 2 h before use) was added to dry THF (34 mL) at 0 °C to form a white suspension. (In this case a yellow suspension often gave low yields of addition product.) The suspension was then heated at 50 °C for 2 h, and the suspension was then cooled to −78 °C. Methylmagnesium bromide (3 M in diethyl ether, 3.4 mL, 10.2 mmol) was added to the white suspension of cerium chloride/THF solution at −78 °C, and the resulting mixture was stirred at this temperature for 1 h. A solution of ketone **28** (487 mg, 1.47 mmol) in THF (10 mL) was added to organocerium reagent via cannula at −78 °C, and the reaction was stirred at this temperature for 1 h. After TLC analysis indicated that all the ketone-spot changed to a polar spot, additional portion of methylmagnesium bromide (3 M in diethyl ether, 3.4 mL, 10.2 mmol) was added, and the reaction mixture was warmed to room temperature for 12 h. After TLC analysis indicated all the pivalate was cleaved (if not, more MeMgBr should be added to the reaction mixture). The reaction mixture was cooled to 0 °C and carefully quenched by addition of saturated $NaHCO_3$. The aqueous layer was extracted with EtOAc (20 mL × 3), washed with brine, and dried over $MgSO_4$. The solution was concentrated to dryness *in vacuo* and the residue was purified by column chromatography (silica gel, EtOAc/hexane 1:5 → 1:2) to give alcohol **29** (323 mg, 83%) as white solid. R_f = 0.26 (EtOAc/hexane 1:1); IRν_{max} (neat, cm^{-1}): 1671, 1121; ^{1}H NMR (400 MHz, $CDCl_3$): δ 1.02 (3H, s), 1.21 (3H, s), 1.30 (1H, ddd, *J* = 13.2, 7.5, 1.4 Hz), 1.72 (1H, dt, *J* = 13.0, 8.9 Hz), 1.81 (1H, ddd, *J* = 13.0, 5.5, 1.6 Hz), 1.93 (1H, d, *J* = 14.2 Hz), 1.98 (1H, dd, *J* = 14.2, 1.6 Hz), 2.10−2.26 (2H, m), 2.59 (1H, dd, *J* = 13.0, 9.4 Hz), 3.06−3.11 (1H, m), 3.53 (1H, s), 4.94 (1H, dt, *J* = 10.0, 1.8 Hz), 4.99 (1H, dt, *J* = 16.9, 1.8 Hz), 5.63 (1H, dt, *J* = 10.0, 3.4 Hz), 5.83−5.91 (m, 2H);^{13}C NMR (150 MHz, $CDCl_3$): δ 18.2 (CH_3), 23.0 (CH_2), 24.9 (CH_2), 31.1 (CH_3), 38.3 (CH), 43.5 (CH_2), 46.3 (CH_2), 46.5 (C), 52.8 (C), 70.6 (C), 79.2 (C), 82.2 (CH), 115.0 (CH_2), 127.8 (CH), 131.4 (CH), 142.8 (CH); HRMS (ESI): calcd for $[C_{16}H_{24}O_3+Na]^+$ 287.1617; found 287.1618: $[\alpha]^{25}_D$ + 23.5 (*c* 0.4, $CHCl_3$).

*1-((1R,3R,3aR,7aS,8S)-8-Hydroxy-7a-methyl-3-vinyl-1,2,3,6,7,7a-hexahydro-1,3a-methanoinden-1-yl)propan-2-one (**32**).* To a solution of alcohol **29** (351 mg, 1.33 mmol) in toluene (17 mL) and THF (5.7 mL) was added at 0 °C lead tetraacetate (1.47 g, 3.3 mmol). The reaction mixture was stirred for 10 min and quenched by addition of saturated

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$NaHCO_3$. The aqueous layer was separated and extracted with EtOAc (10 mL × 3). The combined organic layer was washed with brine and dried over $MgSO_4$. The solution was concentrated to dryness *in vacuo* to give alcohol **30** as yellow oil and used in next steps without purification.

Part of alcohol was purified by passing through a short silica gel column to give colorless oil **30**: R_f= 0.45 (EtOAc/hexane 1:2); IRν_{max} (neat, cm^{-1}): 2959, 1715, 1698, 1652, 1521, 1362, 1171, 1056, 989, 915; ^{1}H NMR (400 MHz, $CDCl_3$): δ 1.23 (3H, s), 1.51 (1H, dd, J = 13.3, 7.8 Hz), 1.96 (1H, dt, J = 13.3, 8.6 Hz), 2.03 (1H, ddd, J = 14.8, 5.3, 1.2 Hz), 2.13 (3H, s), 2.21 (1H, d, J = 14.8 Hz), 2.25−2.43 (2H, m), 2.43 (1H, ABq, dd, J = 17.8 Hz), 2.57 (1H, ABq, d, J = 17.8 Hz), 3.47−3.52 (1H, m), 4.63 (1H, br), 4.98−5.06 (2H, m), 5.15 (1H, dt, J = 9.7, 2.2 Hz), 5.88 (1H, ddd, J = 16.9, 10.0, 8.3 Hz), 6.03 (1H, dt, J = 9.7, 3.5 Hz); ^{13}C NMR (100 MHz, $CDCl_3$) δ 20.3 (CH_3), 24.3 (CH_2), 25.4 (CH_2), 31.7 (CH_3), 37.8 (CH), 44.5 (CH_2), 48.5 (CH_2), 51.4 (C), 65.0 (C), 80.7 (C), 116.0 (CH_2), 122.3 (CH), 134.2 (CH), 141.0 (CH), 197.0 (CH), 210.9 (C); HRMS (ESI): calcd for $[C_{16}H_{22}O_3+Na]^+$ 285.1467; found 285.1467: $[\alpha]^{25}_D$ + 567 (c 0.6, $CHCl_3$).

To a solution of alcohol **30** in dichloromethane (18 mL) were added at 0 °C pyridine (1.6 mL, 20 mmol), 4-dimethylaminopyridine (16 mg, 0.13 mmol) and trifluoroacetic anhydride (0.94 mL, 6.7 mol). The reaction mixture was stirred at 0 °C for 90 min and quenched by addition of water (9 mL). The aqueous layer was extracted with dichloromethane (9 mL × 3) and combined organic layer was washed with brine and dried over $MgSO_4$. The solution was concentrated to dryness *in vacuo* to afford a crude trifluoroacetate as yellow oil. The crude residue was dissolved in dichloromethane (18 mL) and cooled to 0 °C, to which DBU (0.4 mL, 1.2 mmol) was added at 0 °C dropwise. After 15 min the reaction mixture was quenched with 1 *N* HCl. The mixture was extracted with dichloromethane, and the combined organic layer was washed with brine and dried over $MgSO_4$. The solution was concentrated to dryness *in vacuo* to give enone **31** as brown oil, which was used for the next reaction without further purification.

Part of enone was purified by passing through a short silica gel column to give colorless oil of enone **31** as colorless oil: R_f = 0.46 (EtOAc/hexane 1:4); IRν_{max} (neat, cm^{-1}): 2926, 1716, 1687, 1621, 1381, 1209, 1186, 914, 703; ^{1}H NMR (400 MHz, $CDCl_3$): δ 1.06 (3H, s), 1.67 (1H, ddd, J = 13.6, 7.6, 1.1 Hz), 1.94 (1H, dt, J = 13.6, 9.0 Hz), 2.18 (3H, s), 2.23−2.41 (2H, m), 2.90 (1H, dt, J = 20.2, 2.8 Hz), 3.17−3.22 (1H, m), 3.46 (1H, ddd, J = 20.2, 9.5, 2.0 Hz), 5.07 (1H, dt, J = 10.3, 1.5 Hz), 5.13 (1H, dt, J = 17.0, 1.5 Hz), 5.65 (1H, dt, J = 9.9, 2.3 Hz), 5.88 (1H, t, J = 2.3 Hz), 5.94 (1H, ddd, J = 17.2, 10.3, 7.2 Hz), 6.02 (1H, dt, J = 7.0, 3.5 Hz); ^{13}C NMR (100 MHz, $CDCl_3$) δ 23.6 (CH_2), 25.5 (CH_3), 27.8 (CH_2), 31.4 (CH_3), 36.9 (CH_2), 40.4 (CH), 49.8 (C), 63.5 (C), 116.4 (CH_2), 116.9 (CH), 122.9 (CH), 132.6 (CH), 139.8 (CH), 168.4 (C), 198.0 (C), 200.5 (CH); HRMS (ESI): calcd for $[C_{16}H_{20}O_2+H]^+$ 245.1535; found 245.1537: $[\alpha]^{25}_D$ + 308 (c 0.5, $CHCl_3$).

Preparation of Samarium Diiodide in THF. Samarium powder (677 mg, 4.5 mmol) was placed in 50 mL round-bottom flask, to which was added 30 mL of freshly distilled THF under argon atmosphere. To this solution was added diiodomethane (0.24 mL, 3 mmol) dropwise with stirring at the room temperature. In a few minutes later, the solution gradually became blue. The solution was kept stirring at the room temperature for 3 h and eventually the color turned to dark blue, which was immediately used for ketyl radical cyclization.

The freshly prepared samarium diiodide (27 mL) was added dropwise at 0 °C to a solution of aldehyde **31** in a mixed solvent THF (11 mL) and *tert*-butyl alcohol (2.2 mL), while this solution maintain the blue color. After 15 min stirring at 0 °C, the reaction mixture was poured into saturated $NaHCO_3$, and then extracted with EtOAc (5 mL × 3). Combined organic layer was washed with brine and dried over $MgSO_4$. The solution was concentrated to dryness *in vacuo* and the residue was purified by column chromatography (silica gel, EtOAc/hexane 1:10 → 1:5) to give cyclobutane **32** (206 mg, 63%) as colorless oil.

Cyclobutane **32** colorless oil: R_f= 0.58 (EtOAc/hexane 1:1); IRν_{max} (neat, cm^{-1}): 3148, 2920, 1715,1699, 1652, 1541, 1457, 1096, 906, 719; ^{1}H NMR (400 MHz, $CDCl_3$): δ 0.85 (1H, s), 1.21 (1H, dd, J = 12.0, 5.9 Hz), 1.51 (1H, ddd, J = 11.2, 4.2, 1.7 Hz), 1.92−2.06 (2H, m), 2.10−2.16 (2H, m), 2.16 (3H, s), 2.59 (1H, ABq, d, J = 17.6 Hz), 2.69 (1H, ABq, d, J = 17.6 Hz), 2.99−3.04 (1H, m), 3.75 (1H, s), 4.96 (1H, dt, J = 10.4, 2.0 Hz), 5.06 (1H, dt, J = 16.8, 2.0 Hz), 5.74 (1H, dt, J = 10.1, 2.2 Hz), 5.8 (1H, m), 6.0 (1H, ddd, J = 16.8, 10.4, 6.2 Hz); ^{13}C NMR (100 MHz, $CDCl_3$) δ 17.0 (CH_3), 22.1 (CH_2), 26.8 (CH_2), 31.0 (CH_3), 33.8 (CH_2), 39.6 (C), 40.5 (CH), 42.0 (CH_2), 50.2 (C), 55.5 (C), 81.5 (CH), 114.6 (CH_2), 126.4 (CH), 129.4 (CH), 140.8 (CH), 210.6 (C); HRMS (ESI): calcd for $[C_{16}H_{22}O_2+Na]^+$ 269.1512; found 269.1511: $[\alpha]^{25}_D$ + 56.3 (c 0.8, $CHCl_3$).

*(1S,3S,4R,4aR,8aR,9R)-1,3-Dihydroxy-3,8a-dimethyl-9-vinyl-2,3,4,7,8,8a-hexahydro-1H-4a,1-ethanonaphthalen-4-yl Pivalate (**33**).* To a solution of ketone **28** (18 mg, 0.054 mmol) in toluene (0.5 mL) at 0 °C under argon was added a solution of trimethylaluminum (2 M in hexane, 0.16 mL, 0.32 mmol) dropwise. The reaction mixture was allowed gradually to warm to room temperature in 3 h. The mixture was cooled to 0 °C and 5 drops of methyl alcohol was slowly added to this mixture. Then 1 *N* HCl (0.5 mL) was added to the reaction mixture and the resulting solution was extracted with EtOAc (1 mL × 3), washed with brine, and dried over $MgSO_4$. The solution was concentrated to dryness *in vacuo* and the residue was purified by column chromatography (silica gel, EtOAc/hexane 1:5 → 1:2) to give alcohol **33** (14 mg, 75%) as colorless oil. R_f= 0.5 (EtOAc/hexane 1:1); IRν_{max} (neat, cm^{-1}): 3648, 2969, 1716, 1541, 1457, 1158, 1037, 906; ^{1}H NMR (400 MHz, $CDCl_3$): δ 1.03 (3H, s), 1.07 (3H, s), 1.21 (9H, s), 1.31−1.37 (1H, m), 1.78−1.86 (2H, m), 1.95 (1H, d, J = 14.2 Hz), 2.01 (1H, dd, J = 14.2, 1.8 Hz), 2.11 (1H, dt, J = 19.3, 8.4 Hz), 2.30 (1H, dd, J = 19.3, 7.5 Hz), 2.64 (1H, dd, J = 13.0, 9.4 Hz), 3.19−3.24 (1H, m), 4.93 (1H, dd, J = 10.1, 0.8 Hz), 4.99 (1H, dt, J = 7.5, 1.8 Hz), 5.00 (1H, s), 5.51−5.57 (2H, m), 5.82 (1H, ddd, J = 16.9, 9.9, 8.8 Hz); ^{13}C NMR (100 MHz, $CDCl_3$): δ 18.1 (CH_3), 22.7 (CH_2), 25.0 (CH_2), 27.3 (CH_3 × 3), 31.1 (CH_3), 39.2 (C), 40.2 (CH), 43.3 (CH_2), 46.0 (CH_2), 47.0 (C), 51.8 (C), 71.2 (C),79.0 (C), 82.2 (CH), 115.2 (CH_2), 128.0 (CH), 129.2 (CH), 142.4 (CH), 177.0 (C); HRMS (ESI): calcd for $[C_{21}H_{32}O_4+H]^+$ 349.2374; found 349.2375: $[\alpha]^{25}_D$ + 24.3 (c 4.0, $CHCl_3$).

*(2R,4S,4aR,8aR,9S)-8a-Methyl-3-methylene-1-oxo-9-vinyl-2,3,4,7,8,8a-hexahydro-1H-2,4a-methanonaphthalen-4-yl acetate (**36**).* To a solution ketone **34** (83 mg, 0.34 mmol) at 0 °C were added 2,6-lutidine (0.12 mL, 1 mmol) and trimethylsilyl trifluoromethanesulfonate (0.12 mL, 0.7 mmol). The reaction mixture was allowed to gradually warm to room temperature in 90 min, to which saturated $NaHCO_3$ was poured. The aqueous layers was separated and extracted with

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dichloromethane, and the combined organic layer was washed with brine and dried over $MgSO_4$. The solution was concentrated to dryness *in vacuo* to give vinyl silyl ether **35** as yellow oil. The crude vinyl silyl ether was further dissolved in a mixture of acetonitrile (0.5 mL) and dichloromethane (1.5 mL), to which palladium acetate (76 mg, 0.34 mmol) was added at room temperature. After stirring 12 h at room temperature, the solvent was evaporated under reduced pressure. The residue was purified by column chromatography (silica gel, EtOAc/hexane 1:15) to give tricyclic compound **36** (45 mg, 54%) as white solid. R_f= 0.5 (EtOAc/hexane 1:4); IRν_{max} (neat, cm^{-1}): 1742, 1716, 1653, 1521, 1177, 1020, 910; ^{1}H NMR (400 MHz, $CDCl_3$): δ 1.04 (3H, s), 1.71 (1H, ddd, J = 13.8, 7.4, 2.8 Hz), 1.80 (1H, dd, J = 13.8, 8.8 Hz), 2.05 (3H, s), 2.13 (2H, s), 2.19−2.24 (2H, m), 3.19 (1H, s), 5.26 (1H, s), 5.31 (1H, d, J = 1.6 Hz), 5.43 (1H, s), 5.69 (1H, dd, J = 10.1, 2.4 Hz), 5.73 (1H, d, J = 10.1 Hz); ^{13}C NMR (100 MHz, $CDCl_3$): δ 18.2 (CH_3), 21.1 (CH_3), 22.8 (CH_2), 25.1 (CH_2), 34.7 (CH_2), 48.2 (C), 51.6 (C), 59.9 (CH), 79.7 (CH), 114.9 (CH_2), 125.0 (CH), 130.2 (CH), 144.1 (C), 170.5 (C), 213.3 (C); HRMS (ESI): calcd for $[C_{15}H_{18}O_3$+H$]^+$ 247.1329; found 247.1333: $[\alpha]^{25}_D$ + 21.4 (*c* 0.2, $CHCl_3$).

*(3aR,7aR)-3a-((R)-1-(Methoxymethoxy)-3-(trimethylsilyl)-prop-2-yn-1-yl)-7a-methyl-3a,6,7,7a-tetrahydro-1H-inden-1-one (**21**).* To a solution of LDA (1 M in THF, 0.7 mL, 0.7 mmol) at −78 °C was added dropwise a solution of ketone **20** (113 mg, 0.35 mmol) in dry THF (1.5 mL). After stirring for 30 min at −78 °C, a solution of phenylselenenyl chloride (80 mg, 0.42 mmol) in dry THF (1 mL) was added to the enolate solution. The reaction was allowed gradually to warm to room temperature overnight and saturated NH_4Cl was poured into the reaction mixture. The aqueous layer was extracted with EtOAc (2 mL × 3) and the combined organic layer was washed with brine, dried over $MgSO_4$. The solution was concentrated to dryness *in vacuo*. The residue was purified by column chromatography (silica gel, EtOAc/hexane 1:50) to give phenyl selenide **37** (71 mg, 43%).

Phenyl selenide **37**: R_f= 0.48 (EtOAc/hexane 1:10); IRν_{max} (neat, cm^{-1}): 2947, 2371, 1742, 1684, 1647, 1541, 1508, 1250, 1154, 1022, 845, 738, 691; ^{1}H NMR (400 MHz, $CDCl_3$): δ 0.05 (9H, s), 1.12 (3H, s), 1.76 (1H, dd, J = 12.3, 7.2 Hz), 1.91−1.97 (2H, m), 2.21−2.27 (2H, m), 3.01 (1H, dd, J = 14.0, 9.3 Hz), 3.30 (3H, s), 4.22 (1H, s), 4.36 (1H, t, J = 9.2 Hz), 4.49 (1H, ABq, d, J = 6.8 Hz), 4.91 (1H, ABq, d, J = 6.8 Hz), 5.61 (1H, dt, J = 9.6, 3.8 Hz), 5.89 (1H, dt, J = 9.6, 2.2 Hz), 7.26−7.23 (3H, m), 769−7.71 (2H, m); ^{13}C NMR (150 MHz, $CDCl_3$): δ −0.93 (CH_3 × 3), 22.1 (CH_3), 22.8 (CH_2); 23.4 (CH_2), 33.4 (CH_2), 43.4 (CH), 50.5 (C), 51.8 (C), 55.9 (CH_3), 72.9 (CH), 93.6 (CH_2), 97.3 (C), 101.4 (C), 127.8 (CH × 2), 129.0 (CH), 130.3 (C), 132.2 (CH), 134.5 (CH), 215.3 (C); HRMS (ESI): calcd for $[C_{24}H_{32}O_3SeSi$+Na$]^+$ 499.1184; found 499.1180: $[\alpha]^{25}_D$ + 88.7 (*c* 1.75, $CHCl_3$).

This phenyl selenide **37** (42 mg, 0.088 mmol) was dissolved in dichloromethane (2 mL) at room temperature, to which was added hydrogen peroxide (35%, 0.1 mL). The reaction was stirred for 2 h. After TLC analysis indicated that all the starting material was consumed, water (2 mL) was poured into the reaction mixture and the resulting mixture was extracted with dichloromethane (2 mL × 3). The combined organic layer was washed with brine and dried over $MgSO_4$, and the solution was concentrated to dryness *in vacuo*. The residue was purified by column chromatography (silica gel, EtOAc/hexane 1:50) to give enone **21** (25 mg, 92%).

Enone **21**: R_f= 0.47 (EtOAc/hexane 1:10); IRν_{max} (neat, cm^{-1}): 2953, 2856, 2173, 1720, 1249, 1151, 1045, 845; ^{1}H NMR (400 MHz, $CDCl_3$): δ 1.03 (3H, s), 1.77 (1H, ddd, J = 13.6, 7.7, 2.0 Hz), 2.00 (1H, dt, J = 13.6, 8.9 Hz), 2.27−2.33 (2H, m), 3.30 (3H, s), 4.39 (1H, s), 4.44 (1H, Abq, d, J = 6.8 Hz), 4.78 (1H, Abq, d, J = 6.8 Hz), 5.7 (1H, ddd, J = 9.6, 4.1, 3.1 Hz), 6.25 (1H, d, J = 6.0 Hz), 6.27 (1H, dt, J = 9.6, 2.3 Hz), 7.29 (1H, d, J = 6.0 Hz); ^{13}C NMR (100 MHz, $CDCl_3$): δ 0.76 (CH_3 × 3), 22.4 (CH_2), 23.2 (CH_2), 27.5 (CH_3), 53.2 (C), 55.9 (CH_3), 58.6 (C), 79.9 (CH), 93.7 (CH_2), 99.5 (C), 100.2 (C), 128.6 (CH), 130.5 (CH), 134.3 (CH), 156.3 (CH), 208.5 (C); HRMS (ESI): calcd for $[C_{18}H_{26}O_3Si$+H$]^+$ 319.1730; found 319.1727: $[\alpha]^{25}_D$ − 55.5 (*c* 1.7, $CHCl_3$).

*(2R,3R,4R,4aR,8aR,9S)-3-Hydroxy-3,8a-dimethyl-1-oxo-9-vinyl-2,3,4,7,8,8a-hexahydro-1H-2,4a-methanonaphthalen-4-yl Pivalate (**43**).* A solution of ketone **39** (102 mg, 0.31 mmol) in THF (3 mL) at room temperature was mixed with pyrrolidine (0.025 mL, 0.31 mmol). The reaction mixture was stirred for 12 h and the solution was concentrated to dryness *in vacuo*. The residue was purified by column chromatography (silica gel, EtOAc/hexane 1:15 → 1:3) to give ketone **28** (46 mg, 45%) and hydroxyl ketone **43** (39 mg, 38%). Hydroxyl ketone **43**: R_f= 0.38 (EtOAc/hexane 1:2); IRν_{max} (neat, cm^{-1}): 2978, 1735, 1717, 1521, 1397, 1283, 1149, 1055, 1037, 940, 913; ^{1}H NMR (400 MHz, $CDCl_3$): δ 1.15 (3H, s), 1.22 (9H, s), 1.26 (3H, s), 1.62−1.65 (2H, m), 2.12−2.28 (2H, m), 2.77 (1H, s), 3.13−3.16 (1H, m), 5.07 (1H. s), 5.07−5.13 (2H, m), 5.70 (1H, dt, J = 10.0, 3.0 Hz), 5.76 (1H, dt, J = 10.0, 2.1 Hz), 5.98 (1H, ddd, J = 14.9, 10.7, 4.2 Hz); ^{13}C NMR (100 MHz, $CDCl_3$): δ 22.3 (CH_3), 22.8 (CH_2), 24.3 (CH_3), 27.2 (CH_3 × 3), 27.3 (CH_2), 39.0 (C), 47.5 (C), 50.4 (CH), 55.0 (C), 65.5 (CH), 77.2 (C), 87.5 (CH), 116.1 (CH_2), 124.3 (CH), 130.8 (CH), 136.2 (CH), 178.1 (C), 217.2 (C); HRMS (ESI): calcd for $[C_{20}H_{28}O_4$+Na$]^+$ 355.1880; found 355.1879: $[\alpha]^{25}_D$ + 50.3 (*c* 2.5, $CHCl_3$).

*(2aS,2a^{1}R,3R,5aR,7aR,7bS)-5a-Methyl-5-oxo-3-vinyl-3,4,5,5a,6,7,7a,7b-octahydro-2a^{1}H-cyclopenta[h]-cyclopropa[cd]inden-2-yl Acetate (**44**).* To a solution of alkyne **25** (28 mg, 0.1 mmol) in THF (0.5 mL) at room temperature were added chloro(triphenylphosphine)gold(I) (10 mg, 0.02 mmol) and silver tetrafluoroborate (4 mg, 0.02 mmol). The reaction mixture was stirred at room temperature for 3 h and the mixture was quenched by saturated $NaHCO_3$. The mixture was extracted with EtOAc (1 mL × 3) and the combined organic layer was washed with brine, and dried over $MgSO_4$. The solution was concentrated to dryness *in vacuo*. The residue was purified by column chromatography (silica gel, EtOAc/hexane 1:10 → 1:5) to give vinyl acetate **40** (16 mg, 57%). Vinyl acetate **40** (16 mg, 0.057 mmol) was dissolved in methanol (0.5 mL), to which was added potassium carbonate (16 mg, 0.11 mmol) at room temperature. The reaction mixture was stirred for 30 min and then poured into saturated NH_4Cl (1 mL). The mixture was diluted with EtOAc (2 mL) and the aqueous layer was extracted with EtOAc (1 mL × 3). The combined organic layer was dried over $MgSO_4$. The solution was concentrated to dryness *in vacuo*. The residue was purified by column chromatography (silica gel, EtOAc/hexane 1:10 → 1:5) to give diketone **44** (12 mg, 92%). Vinyl acetate **40**: R_f= 0.63 (EtOAc/hexane 1:2); IRν_{max} (neat, cm^{-1}): 2921, 1770, 1737, 1636, 1371, 1199, 1155, 1009, 917, 817; ^{1}H NMR (600 MHz, $CDCl_3$): δ 1.09 (1H, dt, J = 13.6, 9.8 Hz), 1.16 (3H, s), 1.37 (1H, ddd, J = 13.6, 8.9, 1.9 Hz), 1.72 (1H, td, J = 7.0, 2.6 Hz), 1.83−1.94 (4H, m), 2.00 (3H, s), 2.52 (1H, dd, J =

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19.3, 3.9 Hz), 2.64 (1H, dd, J = 19.3, 9.9 Hz), 3.08 (1H, dt, J = 9.9, 3.9 Hz), 5.14 (1H, dt, J = 16.9, 1.2 Hz), 5.17 (1H, dt, J = 10.1, 1.2 Hz), 5.72 (1H, d, J = 2.6 Hz), 6.03 (1H, ddd, J = 16.9, 10.1, 8.8 Hz); ^{13}C NMR (150 MHz, $CDCl_3$): δ 15.6 (CH_2), 19.0 (CH), 19.7 (CH_3), 20.1 (CH), 21.0 (CH_3), 22.0 (CH), 26.7 (CH_2), 41.2 (CH_2), 42.7 (CH), 49.8 (C), 56.9 (C), 110.7 (CH), 116.9 (CH_2), 139.3 ß(CH), 151.9 (C), 167.3 (C), 219.0(C); HRMS (ESI): calcd for $[C_{17}H_{20}O_3+Na]^+$ 295.1305; found 295.1305: $[\alpha]^{25}_D$ − 170.4 (c 0.8, $CHCl_3$).

Diketone **44**: R_f = 0.58 (EtOAc/hexane 1:2); IRν_{max} (neat, cm^{-1}): 2922, 1737, 1266, 1102, 923, 736, 700, 691, 605; ^{1}H NMR (600 MHz, $CDCl_3$): δ 0.93 (1H, ddd, J = 14.3, 11.1, 8.2 Hz), 1.11 (3H, s), 1.21−1.25 (1H, m), 1.49 (1H, dd, J = 14.5, 9.2 Hz), 1.54 (1H, dd, J = 15.2, 6.8 Hz), 1.98−2.05 (1H, m), 2.18 (1H, d, J = 20.4 Hz), 2.49 (1H, dd, 18.7, 2.8 Hz), 2.60 (1H, dd, J = 20.4, 6.8 Hz), 2.87 (1H, dd, J = 18.7, 10.0 Hz), 2.92−2.94 (1H, m), 5.12 (1H, dt, J = 16.8, 1.4 Hz), 5.17 (1H, dt, J = 10.1, 1.4 Hz), 6.00 (1H, ddd, J = 16.8, 10.1, 8.7 Hz); ^{13}C NMR (150 MHz, $CDCl_3$): δ 13.9 (CH_2), 14.6 (CH), 14.8 (CH), 17.5 (CH), 20.1 (CH_3), 27.0 (CH_2), 37.6 (CH_2), 40.9 (CH_2), 42.3 (CH), 50.6 (C), 59.0 (C), 117.6 (CH_2), 139.6 (CH), 217.7 (C), 225.6 (C); HRMS (ESI): calcd for $[C_{15}H_{18}O_2+Na]^+$ 253.1199; found 253.1202: $[\alpha]^{25}_D$ − 7.6 (c 0.6, $CHCl_3$).

*(2R,4S,4aR,8aR,9S)-8a-Methyl-3-methylene-1-oxo-9-vinyl-2,3,4,7,8,8a-hexahydro-1H-2,4a-methanonaphthalen-4-yl Acetate (**46**).* To a solution of alkene **18** (129 mg, 0.3 mmol), sodium carbonate (318 mg, 3 mmol), and urea-hydrogen peroxide (423 mg, 4.5 mmol) in dichloromethane (3 mL) was added dropwise trifluoroacetic anhydride (0.21 mL, 1.5 mmol) at 0 °C. The reaction mixture was stirred at 0 °C for 10 min and 2 mL of water was poured into the reaction mixture. The aqueous layer was separated and extracted with dichloromethane (2 mL × 3), washed with brine, and dried over $MgSO_4$. The solution was concentrated to dryness *in vacuo*. The residue was purified by column chromatography (silica gel, EtOAc/hexane 1:100 → 1:20) to give epoxide **46** (122 mg, 90%) as a single diastereomer. R_f= 0.74 (EtOAc/hexane 1:4); IRν_{max} (neat, cm^{-1}): 1521, 1021, 928; ^{1}H NMR (400 MHz, $CDCl_3$): δ 0.020 (3H, s), 0.028 (3H, s), 0.16 (9H, s), 0.85 (9H, s), 0.88 (3H, s), 1.32 (1H, dd, J = 12.9, 8.7 Hz), 1.53−1.60 (2H, m), 1.69 (1H, tdd, J = 12.6, 5.6, 1.4 Hz), 1.93 (1H, td, 9.2, 4.2 Hz), 2.00 (1H, dd, J = 15.9, 8.0 Hz), 2.20−2.35 (2H, m), 2.97 (1H, d, J = 3.6 Hz), 3.18 (1H, t, J = 3.8 Hz), 3.47 (3H, s), 4.28 (1H, s), 4.72 (1H, ABq, d, J = 6.5 Hz), 4.87 (1H, t, 6.4 Hz), 4.91 (1H, ABq, d, J = 6.5 Hz); ^{13}C NMR (100 MHz, $CDCl_3$): δ −4.7 (CH_3), −4.1 (CH_3), −0.1 (CH_3 × 3), 17.0 (CH_3), 17.9 (C), 21.0 (CH_2), 24.1 (CH_2), 25.8 (CH_3 × 3), 27.4 (CH_2), 32.4 (CH_2), 47.8 (C), 51.7 (C), 52.9(CH), 56.7 (CH_3), 57.7 (CH), 68.4 (CH), 75.8 (CH), 92.9 (C), 95.0 (CH_2), 105.3 (C); HRMS (ESI): calcd for $[C_{24}H_{44}O_4Si_2+Na]^+$ 475.2670; found 475.2670: $[\alpha]^{25}_D$ + 13.6 (c 1.0, $CHCl_3$).

*(1aS,3aR,6aS,6bR)-6a-((S)-1-(Methoxymethoxy)prop-2-yn-1-yl)-3a-methylhexahydro-1aH-indeno[4,5-b]oxiren-4(2H)-one (**47**).* The silyl ether **46** (98 mg, 0.22 mmol) was dissolved in THF (2 mL) and mixed with TBAF (1 M in THF, 0.46 mmol) at 0 °C. The reaction mixture was allowed gradually to warm to room temperature with stirring for 10 h. After TLC analysis indicated that all the silyl group were removed, saturated NH_4Cl was added to quenched the reaction. The aqueous layer was extracted with EtOAc (2 mL × 3), washed with brine and dried over $MgSO_4$. The solution was concentrated to dryness *in vacuo* to give the alcohol as yellow oil. The crude residue was then dissolved in dichloromethane (2 mL) and cooled to 0 °C. Dess-Martin periodinane (151 mg, 0.36 mmol) was added to this alcohol solution, and the reaction mixture was stirred at this temperature for 30 min. Saturated $NaHCO_3$ (2 mL) was added to the reaction mixture and vigorously stirred for few minutes to destroy unreacted Dess-Martin periodinane reagent. The aqueous layer was extracted with dichloromethane (2 mL × 3), washed with brine, and dried over $MgSO_4$. The solution was concentrated to dryness *in vacuo*. The residue was purified by column chromatography (silica gel, EtOAc/hexane 1:5 → 1:2) to give ketone **47** (54 mg, 94%) as colorless oil. R_f= 0.64 (EtOAc/hexane 3:2); IRν_{max} (neat, cm^{-1}): 3258, 2926, 1740, 1215, 1152, 1025, 919, 826; ^{1}H NMR (400 MHz, $CDCl_3$): δ 1.04 (3H, s), 1.31 (1H, dt, J = 14.0, 8.8 Hz), 1.57 (1H, dd J = 14.0, 9.2 Hz), 1.86−2.01 (2H, m), 2.11 (1H, dd, J = 16.4, 8.1 Hz), 2.44 (1H, d, J = 2.4 Hz), 2.47−2.54 (1H, m), 2.74−2.81 (2H, m), 3.05 (1H, d, J = 3.6 Hz), 3.27 (1H, t, J = 4 Hz), 3.47 (3H, s), 4.51 (1H, dd, J = 2.0, 1.8 Hz), 4.70 (1H, ABq, d, J = 6.7 Hz), 4.94 (1H, ABq, d, J = 6.7 Hz); ^{13}C NMR (100 MHz, $CDCl_3$): δ 20.0 (CH_2), 20.1 (CH_2), 20.3 (CH_3), 24.0 (CH_2), 35.1 (CH_2), 47.7 (C), 51.8 (C), 51.9 (CH), 55.6 (CH), 56.4 (CH_3), 65.9 (CH), 79.5 (CH), 80.5 (C), 94.6 (CH_2), 215.9 (C); HRMS (ESI): calcd for $[C_{15}H_{20}O_4+Na]^+$ 287.1259; found 287.1260: $[\alpha]^{25}_D$ + 45.4 (c 0.9, $CHCl_3$).

*(2S,3R,6aR,9aS)-2-hydroxy-3-(Methoxymethoxy)-2,6a-dimethyl-2,3,4,5,6a,7-hexahydroindeno[4,3a-b]furan-6(9aH)-one (**48**).* To a solution of alkyne **47** (22 mg, 0.083 mmol) in 1.1 mL of THF/water (10:1) at room temperature were added chloro(triphenylphosphin)gold(I) (4 mg, 0.008 mmol) and silver trifluoromethanesulfonate (3 mg, 0.012 mmol). The reaction mixture was heated to 70 °C for 80 min. After TLC analysis indicated that all the starting material was consumed, the reaction was cooled to room temperature. Saturated $NaHCO_3$ was added to the reaction mixture and the aqueous layer was extracted with EtOAc (1 mL × 3), washed with brine, and dried over $MgSO_4$. The solution was concentrated to dryness *in vacuo*. The residue was purified by column chromatography (silica gel, EtOAc/hexane 1:3 → 1:1) to give tricyclic compound **48** (17 mg, 76%) as white solid. R_f= 0.51 (EtOAc/hexane 3:2); IRν_{max} (neat, cm^{-1}): 3648, 2927, 1736, 1399, 1086, 1045, 1029, 1015, 890, 807, 704; ^{1}H NMR (400 MHz, $CDCl_3$): δ 1.10 (3H, s), 1.51 (3H, s), 1.85−1.93 (2H, m), 2.16 (1H, dt, J = 12.9, 9.0 Hz), 2.30 (1H, ddd, J = 19.4, 18.2, 8.6, Hz), 2.55 (1H, dd, J = 19.4, 9.0 Hz), 2.97 (1H, d J = 18.5 Hz), 3.30 (3H, s), 3.77 (1H, br), 3.79 (1H, s), 4.35 (1H, br), 4.41 (1H, ABq, d, J = 7.0 Hz), 4.49 (1H, ABq, d, J = 7.0 Hz), 5.78−5.81 (1H, m), 5.83−5.87 (1H, m); ^{13}C NMR (100 MHz, $CDCl_3$): δ 22.4 (CH_3), 28.9 (CH_3), 31.5 (CH_2), 31.8 (CH_2), 33.5 (CH_2), 50.6 (C), 53.9 (C), 56.9 (CH_3), 79.1 (CH), 87.9 (CH), 96.5 (CH_2), 104.8 (C), 129.2 (CH), 129.7 (CH), 216.3 (C); HRMS (ESI): calcd for $[C_{15}H_{22}O_5+Na]^+$ 305.1359; found 305.1360: $[\alpha]^{25}_D$ + 2.4 (c 1.0, $CHCl_3$).

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.joc.6b02886.

H- and C NMR spectra, X-ray crystallographic analyses, and experimental details (PDF)

X-ray cystallographic data for compounds **29**, **36**, and **48** (CIF)

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Notes

The authors declare no competing financial interest.

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(16) Triethyl amine was necessary as the base for acylation to obtain **26** in 74% yield. A stronger amine base such as $^{i}Pr_2N$-Et afforded a vinyl pivalate.

(17) Compound **11** (R= H, R′= Ac) was converted to **10** (R= H, R′= Ac) in 60% yield with $Hg(OTFA)_2$ in TFA/H_2O at 0 °C for 1 h. See ref 8. The presence of C6-vinyl group (**25**) affected big difference in the oxymercurative ring cyclization to give **27**.

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