Articles

Carbocationic Rearrangements of Silphinane Derivatives

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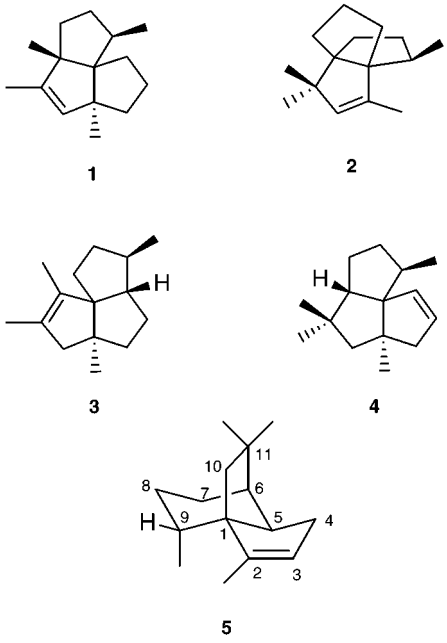
Solvolysis of silphin-1α and -1*β*-yl mesylates (**18α**-OMs and **18*β***-OMs) gave rise to mixtures of silphinene (**4**), bridgehead alcohol **22**-OH (or its acetate), and α-terrecyclene (**5**) accompanied by trace amounts of isocomene (**1**) and modhephene (**2**). The 10^3 higher solvolysis rate determined for **18α**-OMs over its epimer signifies a concerted rearrangement to a more stable tertiary bridgehead carbocation (**36**) which undergoes a second rearrangement and elimination to α-terrecyclene (**5**) (see Scheme 5 in the paper). Isocomene and modhephene presumably arise from a minor competing pathway resulting from 7→1 hydride shift to the silphin-7-yl ion (**38** ≡ **11**) which partitions between methyl and cyclopentane ring rearrangements. Acetolysis of secosilphinyl nosylate **21** (X = ONs) is accompanied by *π* participation leading directly to **38** and from there to a 2:1 mixture (6%) of isocomene and modhephene. $TiCl_4$-mediated heterolysis of silphin-1α-yl trifluoroacetate (**18α**-O_2CCF_3) initiates a complex rearrangement pathway to 3-chloro-1,4,4,11-tetramethyltricyclo[5.3.1.$0^{3,8}$]-undecane (**24**). α-Terrecyclene (**5**) was converted to various oxygenated terrecyclane derivatives by dihydroxylation, hydroboration, and epoxidation (see Scheme 3 in the paper) and to its exocyclic isomer *β*-terrecyclene (**34**, see Scheme 4 in the paper). The observed rearrangements of the silphinyl mesylates (see Scheme 5 in the paper) afford chemical precedent for a biogenetic pathway that links terrecyclanes (e.g. quadrone), isocomene, and modhephene to the silphinane family of cyclopentanoid sesquiterpenes formally derivable from caryophyllene (see Scheme 1 in the paper).

The isolation and structure elucidation of isocomene (**1**, Chart 1)[1] and modhephene (**2**)[1b,2−4] by L. Zalkow, F. Bohlmann, and associates heralded the subsequent discovery of not only numerous analogues and oxidized metabolites[5−7] but also several different skeletal types of tricyclopentanoid sesquiterpenes, including the silphiperfolene isomers (e.g. **3**)[4,8] and silphinene (**4**).[4,5b,9,10] These novel structures raise interesting questions concerning the biogenetic origins and relationships of these natural products.[11] The early suggestion that **1** and **2** can be derived from a common silphin-7-yl carbocation (**11**) by 1,2-methyl shift and trimethylene ring migration[1b] has been validated by acid-catalyzed interconversions

Chart 1. Structures of Triquinane Sesquiterpenes



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(1) (a) Zalkow, L. H.; Harris, R. N., III; Van Derveer, D.; Bertrand, J. A. *J. Chem. Soc. Chem. Commun.* **1977**, 456−457. (b) Zalkow, L. H.; Harris, R. N., III; Burke, N. I. *J. Nat. Prod.* **1979**, *42*, 96.

(2) Zalkow, L. H.; Harries, R. N., III; Van Derveer, D. *J. Chem. Soc., Chem. Commun.* **1978**, 420−421.

(3) Bohlmann, F.; LeVan, N.; Pickard, J. *Chem. Ber.* **1977**, *110*, 3777−3781.

(4) (a) Bohlmann, F.; Jakupovic, J. *Phytochemistry* **1980**, *19*, 259−265. (b) Bohlmann's biogenetically consistent numbering system for presilphiperfolanes, silphiperfolanes, and silphinanes seems to be generally accepted for these three sesquiterpene families: see *Dictionary of Natural Products*; Chapman and Hall: London, 1994; Vol. 7, p xxvii. In view of the biogenetic connections discussed in this paper, we recommend its logical extension to the isocomane and modhephane families also.

(5) (a) Bohlmann, F.; LeVan, N.; Pham, T. V. C.; Jakupovic, J.; Schuster, A.; Zabel, V. Watson, W. H. *Phytochemistry* **1979**, *18*, 1831. (b) Teresa, J. D. P.; Feliciano, A. S.; Barrero, A. F.; Medarde, M.; Tomé, F. *Phytochemistry* **1981**, 20, 166−167.

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(7) Modhephene metabolites: (a) Reference 6a. (b) Bohlmann, F.; Ahmed, M.; Borthakur, N.; Wallmeyer, M.; Jakupovic, J.; King, R. M.; Robinson, H. *Phytochemistry* **1982**, *21*, 167.

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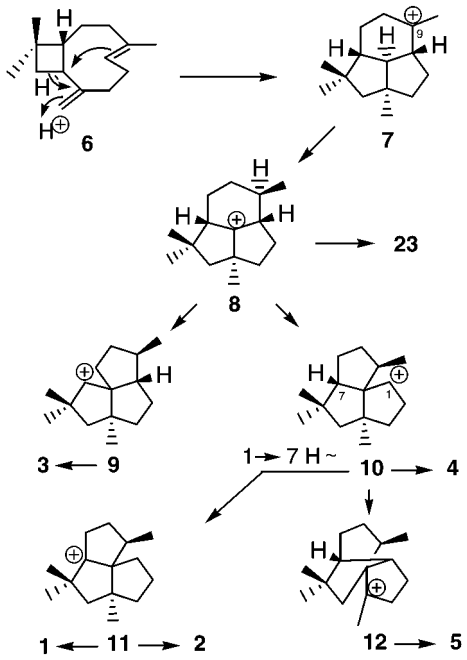
Scheme 1. Biogenesis of Triquinane Sesquinane Sesquiterpenes



and cascade rearrangements from dispiro[3.0.4.2]undecanols.[12] The co-occurrence of the silphiperfolenes (e.g. **3**) and silphinene (**4**) with caryophyllene[4] led Bohlmann to propose a biogenetic pathway by ring expansion of the caryophyllenyl ion (**6**), π cyclization, and hydride shift to generate the presilphiperfolan-8-yl ion **8** as a key branchpoint intermediate (Scheme 1).[4] A similiar scheme was postulated independently by Hanson in connection with studies on botrydial biosynthesis.[13] The structures of presilphiperfolan-8-ol (**23**)[6c,14,15] and the recently discovered 9-ol isomer[8f,15] corresponding to hydration of ions **8** and **7**, respectively, provided support for this hypotheses. The results of isotope labeling experiments[16] on the biosynthesis of botrydial[17] afford experimental evidence in accord with this scheme and in particular demonstrate the occurrence of an 8,9 hydride shift[16b] in the formation of the presumed presilphiperfolan-8-ol intermediate (**23**).

The solvolytic rearrangement of silphin-1α-yl methanesulfonate (**18α**-OMs) to α-terrecyclene (**5**) discovered in these laboratories[18] led to the suggestion that the ethanoindane skeleton of quadrone,[19] terrecyclic acid,[20] and related fungal metabolites[21] might be formed by a similar silphinyl to terrecyclanyl rearrangement.[22] The Bohlmann and Zalkow biogenetic schemes can be connected by invoking a 1,3-hydride shift to convert the silphin-1-yl ion (**10**) to its 7-yl isomer (**11**), thereby encompassing isocomene and modhephene in this group of caryophyllene-derived sesquiterpenes. The acid-catalyzed conversion of (−)-silphinene to (−)-isocomene and (−)-modhephene[23] presumably takes place by C7−C1 hydride shift, providing chemical precedent for this remaining linkage in Scheme 1.

In view of the key branchpoint position of the silphin-1-yl ion in these plausible biogenetic pathways to **1**−**4**, we have undertaken further investigation to evaluate the reactivity of isomeric silphinyl derivatives and the competing rearrangements they undergo. In this paper, we report the rates and products from solvolysis of silphin-1α-yl and -1*β*-yl methanesulfonates (**18α**- and **18*β***-OMs) as well as π cyclizations of 1,8-*seco*-silphinyl *p*-nitrobenzenesulfonate (**21**-ONs). A multistep Lewis-acid mediated rearrangement of silphin-1α-yl trifluoroacetate (**18α**-O_2CCF_3) to 1,4,4,11-tetramethyltricyclo[5.3.1.$0^{3,8}$]undecane derivatives is described. The structure of α-terrecyclene (**5**) is established by an X-ray diffraction analysis of **31** (R = H), and various terrecyclane derivatives are characterized.

Synthesis of (±)-Silphin-1-ols and Secosilphinol. (±)-Silphinene (**4**) was prepared in two steps according to Wender's photoannulation approach[24] by irradiation of arene **13** and lithium/ethylamine reduction of the resulting 1:1 mixture of cyclosilphinene **15** and isomer **14** (Scheme 2). The difficult separation of **14** and **15** by chromatography on $AgNO_3$-impregnated silica gel proved unnecessary because **14** underwent complete reduction to saturated tricycle **16** under the lithium/ethylamine conditions. Epoxidation (*m*CPBA, CH_2Cl_2) of **4** (as a mixture with about 10% of the silphin-2-ene isomer and **16**) afforded a 3:1 mixture of **17α** and **17*β*** epoxides which was reduced ($LiAlH_4$, THF) to the chromatographically separable silphinol isomers, **18α**-OH (57%) and **18*β***-OH

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(10) For reviews on cyclopentanoid natural products, see: (a) Paquette, L. A. *Top. Curr. Chem.* **1979**, *79*, 41−152; **1984**, *119*, 1−147. (b) Paquette, L. A.; Doherty, A. M. *Polyquinane Chemistry*; Springer-Verlag: Berlin, 1987.

(11) For reviews and leading references on sesquiterpene biosynthesis, see: (a) Cane, D. E. *Chem. Rev.* **1990**, *90*, 1089−1103. (b) Cane, D. E. *Acc. Chem. Res.* **1985**, *18*, 220. (c) Cane, D. E. In *Biosynthesis of Isoprenoid Compounds*; Porter, J. W., Spurgeon, S. L., Eds. Wiley: New York, 1981; Vol. 1, Chapter 6.

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(15) Weyerstahl, P.; Marschall, H. Schulze, M.; Schwope, I. *Liebigs Ann. Chem.* **1996**, 799−807.

(16) (a) Bradshaw, A. P. W.; Hanson, J. R.; Nyfeler, R. *J. Chem. Soc., Perkin Trans. 1* **1981**, 1469−1472. (b) Bradshaw, A. P. W.; Hanson, J. R.; Nyfeler, R.; Sadler, I. H. *J. Chem. Soc., Perkin Trans. 1* **1982**, 2187−2192.

(17) Fehlhaber, H.-W.; Geipel, R.; Mercker, H.-J.; Tschesche, R.; Welmar, K. *Chem. Ber.* **1974**, *107*, 1720−1730. (b) Lindner, H. J.; Gross, B. v. *Chem. Ber.* **1974**, *107*, 3332−3336.

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(19) (a) Ranieri, R. L.; Calton, G. J. *Tetrahedron Lett.* **1978**, 499−502. (b) Calton, G. J.; Ranieri, R. L.; Espenshade, M. A. *J. Antibiotics* **1978**, *31*, 38.

(20) Nakagawa, M.; Hirota, A.; Sakai, H.; Isogai, A. *J. Antibiotics* **1982**, *35*, 778.

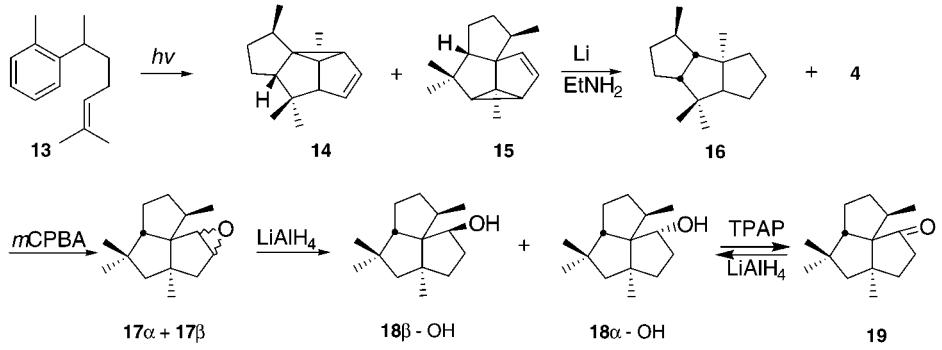
(21) Hirota, A.; Nakagawa, M.; Sakai, H.; Isogai, A. *J. Antibiotics* **1982**, *35*, 783.

(22) We propose the semisystematic name terrecyclane as the parent hydrocarbon for this family of tricarbocyclic sesquiterpenes. The positional numbering shown for α-terrecyclene (**5**) appears to be generally consistent with IUPAC guidelines and is recommended instead of that originally proposed for quadrone.[19a]

(23) Fitjer, L.; Monzó-Oltra, H. *J. Org. Chem.* **1993**, *58*, 6171−6173.

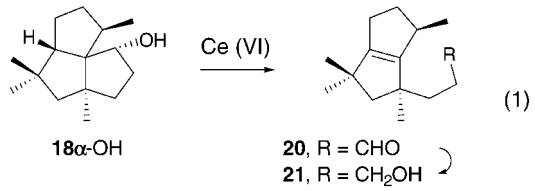
(24) (a) Wender, P. A.; Ternansky, R. J. *Tetrahedron Lett.* **1985**, *26*, 2625−2628. (b) Coates, R. M.; Ho, Z.; Zhu, L. *J. Org. Chem.* **1996**, *61*, 1184.

Scheme 2. Synthesis of Siphin-1α- and -1*β*-ols and Silphinone



(21%). The stereochemistry of the major isomer (mp 51−53 °C) was established by single-crystal X-ray diffraction. The opposite configuration of the hydroxyl group had been originally assigned in the literature based on ^{1}H NMR spectral differences for the isomers.[4a] Oxidation of either **18**α-OH or **18*β***-OH with tetrapropylammonium perruthenate (TPAP, NMO, CH_2Cl_2)[25] gave silphin-1-one (**19**) in high yield, and its reduction with $LiAlH_4$ afforded **18*β***-OH and **18**α-OH in a 6:1 ratio.

Oxidation of **18**α-OH or **18*β***-OH with ceric ammonium nitrate in aqueous acetonitrile effected cleavage to bicyclic enal **20** (65%, eq 1), analogous to a similar oxidation of borneol to campholenic aldehyde.[26]



(1)

$LiAlH_4$ reduction of **20** afforded secosilphinol **21**-OH. In an alternative approach to ring cleavage, irradiation of **19** proceeded with decarbonylation and *β*-hydrogen transfer to give (1*S**,6*R**)-1,2,3,4,5,6-hexahydro-1-vinyl-1,3,3,6-tetramethylpentalene, rather than the desired enal **20**.[27]

Solvolysis Reactions. Solvolyses of silphin-1α- and -1*β*-yl methanesulfonates (**18**α- and **18*β***-OMs) were conducted in 75% aqueous acetone with pyridine as buffer. The rates were measured by ^{1}H NMR spectroscopy in 3:1 acetone-d_6/D_2O at 25 °C (**18**α-OMs) and at 70 and 110 °C (**18*β***-OMs) (Table 1). The α-mesylate proved to be ca. 10^3 more reactive than the *β*-isomer.

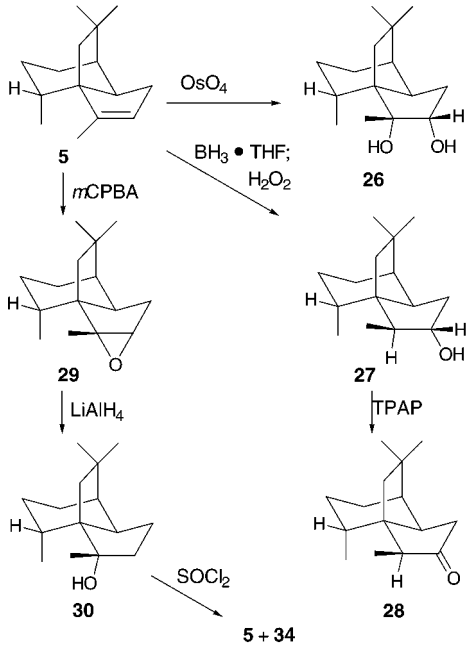
The products obtained from hydrolysis, formolysis, and acetolysis of **18**α-OMs, and from hydrolysis of the less reactive **18*β***-OMs are presented in Table 2. In all cases the major olefin product was α-terrecyclene (**5**, 36−84%) which was accompanied by significant proportions of silphinene (**4**, 10−33%). Trace amounts (ca. 0.4%) of isocomene (**1**) and modhephene (**2**) were also detected and identified by GC and GC/MS comparisons with authentic samples of these sesquiterpenes.[28,29] The structure of α-terrecyclene is based upon the chemical transformations given below (Schemes 3 and 4) and a single-crystal X-ray crystallographic analysis of **31** (R = H).

Table 1. Solvolytic Rates[a] of Silphin-1α- and -1*β*-yl Methanesulfonates (18α-OMs and 18*β*-OMs) in 3:1 Acetone-d_6/D_2O

	t (°C)	$k_{obs} \times 10^5$ (s−1)	
18α-OMs	25	310 ± 20	(1.0)
18*β*-OMs	110	56 ± 2	
	70	6.6 ± 0.3	
	25[b]	0.30 ± 0.05	∼ 0.001

[a] Rates were determined by ^{1}H NMR spectroscopy. The average of two runs is shown in the column. The error estimate is the deviation from the average. [b] The rate was estimated by extrapolation.

Scheme 3. Oxidative Functionalization of α-Terrecyclene



The major alcohol formed in hydrolyses of the α and *β* methanesulfonates is assigned as 2,2,4,7-tetramethyltricyclo[5.4.0.0^{4,8}]undecan-8-ol (**22**-OH, Chart 2) based on consistent ^{1}H and ^{13}C NMR spectral data, ^{1}H−^{1}H COSY and ^{1}H−^{13}C HETCOR NMR plots, IR, and MS data together with its origin in the solvolytic rearrangement. Attempts to detect presilphiperfolan-8-ol (**23**) in the alcohol fractions by means of chromatographic and spectral comparisons with the natural product[14] were

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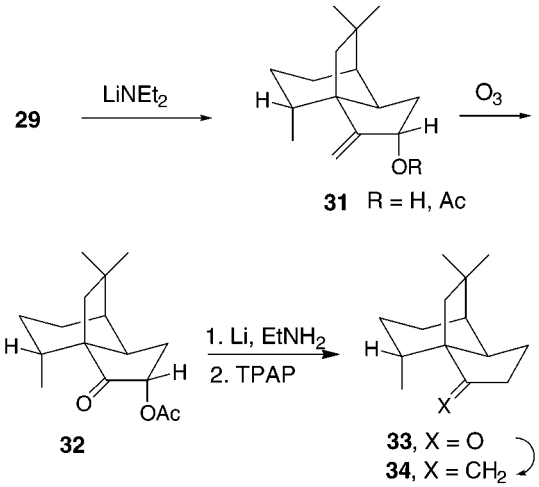
(28) (±)-Isocomene was synthesized according to literature procedures: Pirrung, M. C. *J. Am. Chem. Soc.* **1981**, *103*, 82−87.

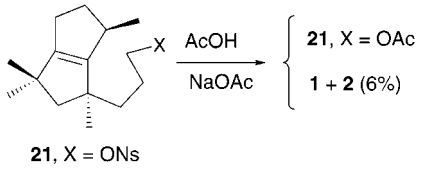
(29) Curran, D. P.; Shen, W. *Tetrahedron* **1993**, *49*, 755. We are grateful to Professor Curran for providing a sample of (±)-modhephene for these comparisons.

Scheme 4. Conversion of α-Terrecyclene Epoxide to *β*-Terrecyclene



unsuccessful (the detection limit was estimated to be ~0.5%). A similar product distribution of olefins and acetates including the tricyclic bridgehead acetate (**22**-OAc, 3%) was formed in acetolysis of **18**α-OMs. On the other hand, formolysis of **18**α-OMs afforded α-terrecyclene in 84% yield.

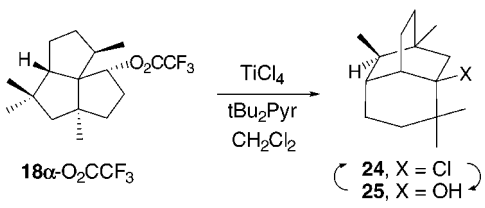
Acetolysis of secosilphinyl nosylate **21** (X = ONs) in acetic acid (NaOAc, 60 °C) (eq 2) was carried out



(2)

according to a literature procedure for solvolytic cyclization of campholenyl nosylate to camphene (68%).[30] Although the major product proved to be acetate (**21**, X = OAc; 78%), a 2:1 mixture of isocomene and modhephene was also obtained in 6% yield. The isomeric olefins were partially separated from each other (enrichment to ~80−85%) by flash chromatography on $AgNO_3$-impregnated silica gel and were identified by GC, GC/MS, and ^1H NMR comparisons with authentic samples.[28,29]

$TiCl_4$-Mediated Rearrangement of Silphin-1α-yl Trifluoroacetate. A complex rearrangement of the silphinyl nucleus was discovered when **18**α-O_2CCF_3 was exposed to $TiCl_4$ (3 equiv) and 2,6-di-*tert*-butylpyridine (6 equiv) in CH_2Cl_2 (−78 °C, 1 h) (eq 3). The tertiary



(3)

chloride product (**24**) obtained in high yield underwent solvolysis in 75% aqueous acetone (pyridine buffer, 70 °C, 4 h) to a crystalline tertiary alcohol which was converted back to the same chloride with $SOCl_2$ (CH_2Cl_2, 25 °C). The structure of the alcohol as 1,4,4,11-tetramethyltricyclo[5.3.1.$0^{3,8}$]undecan-3-ol (**25**) was established by single-crystal X-ray diffraction analysis. No intermediates between **18**α-O_2CCF_3 and **24** were detected when rearrangements were interrupted at partial conversion or when reactions were performed with variable proportions of Lewis acid and base.

Terrecyclene Derivatives. α-Terrecyclene (**5**) was converted to a number of oxygenated derivatives and into *β*-terrecyclene (**34**) in order to confirm the structure and to characterize compounds which might be oxidative metabolites or intermediates in the biosynthesis of quadrone or related fermentation products of *Aspergillus terreus*. (Schemes 3 and 4).[19−22] Osmylation, hydroboration, and epoxidation of **5** afforded diol **26**, secondary alcohol **27**, and epoxide **29**, respectively, as single isomers. The stereochemistry of **26** and **27** is assumed to be the same as that of **29** which was proven by the X-ray determination with **31** (R = H). Evidently the ethano bridge and its geminal methyl groups block the approach of reagents from the *β*-face of α-terrecyclene. TPAP oxidation[25] of **27** gave terrecyclan-3-one (**28**). $LiAlH_4$ reduction of **29** afforded terrecyclan-2α-ol (**30**) which underwent dehydration ($SOCl_2$, pyr) to a 4:1 mixture of α- and *β*-terrecyclenes (**5** + **34**).

Pure *β*-terrecyclene was obtained in seven steps from epoxide **29** (Scheme 4). *β*-Elimination with $LiNEt_2$ furnished the crystalline α-methylene alcohol **31** (R = H), the X-ray diffraction analysis of which confirmed the structure and stereochemistry of these terrecyclane derivatives. Ozonolysis of the corresponding acetate (**31**, R = Ac) followed by reductive cleavage and reoxidation provided norterrecyclan-2-one (**33**). Wittig methylenation ($Ph_3P^+CH_3Br^-$, KOtBu, THF)[31] gave *β*-terrecyclene **34** (60%).

Discussion

A mechanism for the solvolysis of silphin-1α-yl mesylate (**18**α-OMs) is outlined in Scheme 5. The 62:1 ratio (**5** + **22**-OH)/(**1**+**2**) from the aqueous solvolysis corresponds to a free energy difference $\Delta\Delta G^{\ddagger} \approx 2.8$ kcal/mol in the competition between Wagner−Meerwein rearrangement to the tricyclo[5.4.0.$0^{4,8}$]undec-8-yl ion **36** and the C7→Cl hydride shift to the silphin-7-yl ion (**38** ≡ **11**) which then undergoes further rearrangements to isocomene and modhephene. The similarity of the product distributions from the epimeric silphinyl mesylates indicates common carbocation intermediates. However, the 1000-fold higher reactivity of the α mesylate presumably reflects *σ* participation and concerted rearrangement to the more stable tertiary ion **36**. The 13-fold lower **18**α-OMs/**18***β*-OMs rate ratio compared to 1.3×10^4 exo/endo rate ratio for acetolysis of 1-methyl-2-norbornyl tosylates[32] may be attributed to an increase in strain energy in the rearrangement to **36**. Thus, molecular mechanics calculations for the parent tricyclic hydrocarbons[33] show norsilphinane (SE = 17.4 kcal/mol), to be less strained by 1.9 kcal/mol than tricyclo[5.4.0.$0^{4,8}$]undecane (SE = 19.3 kcal/mol) the parent ring system corresponding to **22**-OH. Although **36** no doubt bears some additional

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Table 2. Products from Solvolyses of Silphin-1α- and -1*β*-yl Methanesulfonates (18α-OMs and 18*β*-OMs)

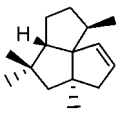
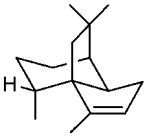
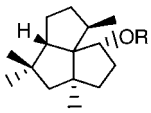
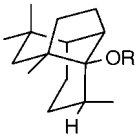
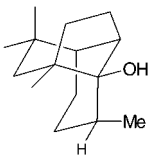
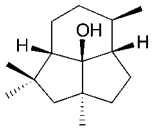
methane-sulfonate	conditions: solvent	conditions: *t* (°C)	olefin products (%)			alcohols or acetates (%)	
					others		
18α-OMs	75% aq acetone	25	24	36	**1** (~0.4) **2** (~0.4)	3 (R = H)	13 (R = H)
	HCO_2H	25	10	84			
	CH_3CO_2H	25	21	39		1 (R = Ac)	3 (R = Ac)
18*β*-OMs	75% aq acetone	75	33	40	**1** (~0.4) **2** (~0.4)	2 (R = H)	17 (R = H)

Chart 2. Structures of Tricyclic Alcohols



22 - OH



23

strain resulting from the bridgehead location of the sp^2 carbon,[34] it is simply a bridged version of the bicyclo-[3.3.1]non-1-yl carbocation.[35] The latter species, albeit 8.3 kcal/mol more strained than the parent hydrocarbon,[34b] is formed readily in solvolyses of the corresponding bridgehead chloride and bromide which proceed only 60−100 times more slowly than the relevant *tert*-butyl halide.[35]

The solvolytic cyclization of nosylate **21** provided an independent route to the silphin-7-yl carbocation **38** (≡ **11**). Evidently this species undergoes relatively rapid methyl group and ring methylene rearrangements leading to isocomene and modhephene, respectively, for no products derived from **38** or other potential intermediates were detected.

The $TiCl_4$-induced transformation of silphin-2α-yl trifluoroacetate to tricyclic chloride **24** (eq 3) obviously entails a complex, multistep pathway. Since the tricyclo-[6.3.0.$0^{3,8}$]undecane parent hydrocarbon related to silphinane is 5.11 kcal/mol more strained than tricyclo-[5.3.1.$0^{3,8}$]undecane,[33] the relief of strain energy is probably an important thermodynamic driving force for this rearrangement. The nine-step pathway illustrated in Scheme 6 is the simplest mechanistic pathway found by trial-and-error and by computer searching using the ICAR program for carbocation rearrangements.[36] Although 1,3-hydride rearrangements similar to those shown in Scheme 6 occur readily in bicyclo[3.2.1]octyl carbocations,[37] molecular models indicate that the tricyclic ethano-bridged ions are restricted to more rigid conformations in which the alignment of the relevant C−H bonds for intramolecular hydrogen transfer appears less favorable. Alternatively, equivalent interconversions might take place by intermolecular hydrogen transfers. It is remarkable that the **18α**-O_2CCF_3→**24** conversion occurs without detectable accumulation of any intermediates.

The facility of the double Wagner−Meerwein rearrangement of the silphinyl ion to α-terrecyclene (**5**) under the solvolytic conditions supports a biogenetic connection between silphinene, quadrone, and structurally related *A. terreus* metabolites. Thus, the latter ethano-bridged indane natural products may belong to the same family of caryophyllene-derived sesquiterpenes. The absolute configurations of presilphiperfolanol (**23**),[14] silphinene (**4**),[23] and the known terrecyclanes[38] are consistent with a common biogenetic origin. Although all isotope labeling results from studies on terrecyclane biosynthesis[38,39] are consistent with this hypothesis, an alternative scheme originating from humulene[39] is equally compatible with the biosynthetic data, and therefore this option cannot be excluded at this time.

The formation of isocomene and modhephene in the solvolytic rearrangements of the silphinyl mesylates and from acid-catalyzed conversion of silphinene[23] provides experimental precedent for a biogenetic linkage of these triquinane sesquiterpenes. If these speculations prove to be correct, the silphin-1-yl and -8-yl ions (**10** and **11**) represent further branch points in the cascade of rearrangements that generate the various cyclopentanoid structures.

Experimental Section

General Aspects. Melting points were determined in open-ended capillaries and are uncorrected. ^1H and ^{13}C NMR spectra were recorded in $CDCl_3$ at 400 and 100 MHz, respectively, unless specified otherwise. *J* values are given in Hz. GC analyses were carried out with a 30-m RTX-5 fused silica capillary column using helium as a carrier gas and flame ionization detection. Flash chromatography[40] was performed on Woelm 32−64 mm silica gel. $AgNO_3$-impregnated silica gel (15%, w/w) was prepared by a literature procedure.[41] All reactions, except those carried out in aqueous solvents, were performed under N_2. Solutions were usually concentrated with a rotary evaporator at 15−20 Torr after being dried ($MgSO_4$).

(*E*)-2-Methyl-6-(2′-methylphenyl)-2-heptene (13). This procedure was based on literature methods.[24,42] A suspension

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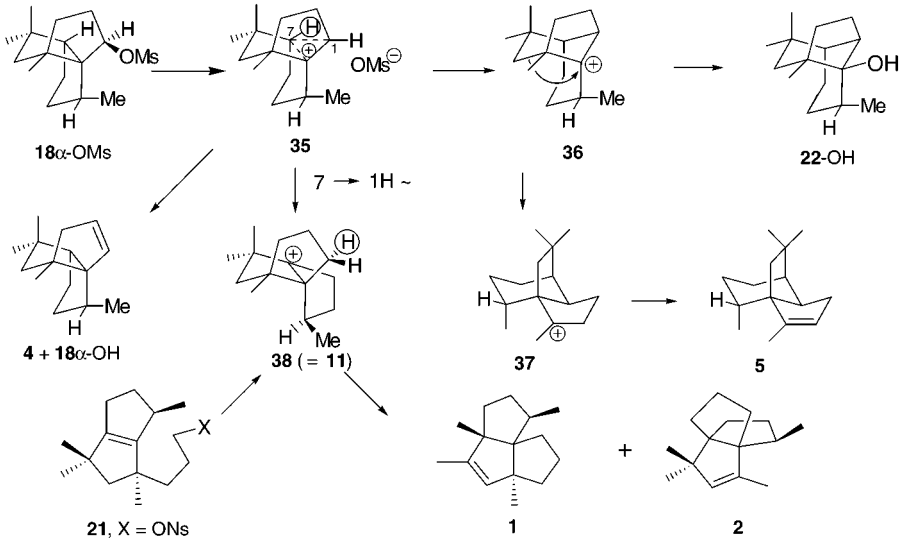
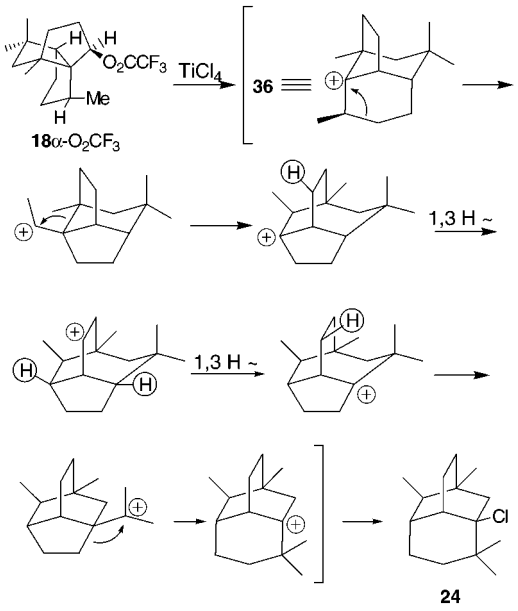
Scheme 5. Mechanism of Silphinyl Mesylate Solvolytic Rearrangements



Scheme 6. Proposed Mechanism for the $TiCl_4$-Induced Rearrangement



of small Li pieces (32.1 g, 4.63 mol) and dry ether (900 mL) under N_2 in a 2-L flask equipped with a thermometer to monitor the internal temperature was stirred mechanically at room temperature as 2-bromotoluene (99.0 g, 0.579 mol) in ether (150 mL) was slowly added. After 1 h at reflux a solution of 6-methyl-5-hepten-2-one (40.0 g, 0.317 mol) in ether (150 mL) was added slowly. The reaction mixture was stirred and heated at reflux for an additional 1 h and then cooled to −78 °C. NH_3 (about 400 mL) was carefully condensed into the ethereal suspension of lithium metal and alkoxide at −78 °C for 20−30 min, during which a dark blue color was established. The progress of the reduction was followed by TLC. After 3.5 h, methanol was cautiously added at low temperature in portions to discharge the blue color, and the reaction mixture was allowed to warm to room temperature and stirred for 1 h. In addition, acetic acid in ether (ca. 20 mL) was added to ensure that the excess lithium was destroyed. The mixture was stirred vigorously for another hour at room temperature, and the remaining NH_3 was allowed to evaporate. **Caution!** *It is essential that all remaining lithium metal be consumed before water is added.* The residue was partitioned between ether (500 mL) and water (1000 mL). The aqueous solution was extracted with ether (3 × 500 mL). The combined organic layers were dried ($MgSO_4$), and solvent was evaporated under reduced pressure to give a crude yellow oil (85 g). Purification by fractional distillation to afforded arene **13** (61.3 g, 0.303 mol, 96% based on ketone): bp 67−69 °C (0.3 mm). IR (neat): 3019, 2967, 2924, 2860, 1489, 1456, 1375, 1092, 1032, 985, 830 cm^{-1}. ^1H NMR: δ 1.49 (s, 3H), 1.62 (16 line m, 2H), 1.66 (d, 3H, J = 1.0), 1.92 (AB ddq, 2H, J = 14.6, 7.3), 2.29 (s, 3H), 2.96 (sextet, 1H, J = 7.1), 5.04 (t sept, 1H, J = 7.3, 1.0), 7.03−7.20 (18 line m, 4H). ^{13}C NMR: δ 17.50, 19.42, 21.58, 25.65, 26.05, 33.77, 37.65, 124.47, 125.13, 125.29, 126.04, 130.03, 131.41, 135.28, 145.65. Anal. Calcd for $C_{15}H_{22}$: C, 89.04, H, 10.96. Found: C, 89.11; H 10.92.

(2α,7,7,11β-Tetramethyl-6β,8βH-tetracyclo[6.3.0.0.^{1,3}0^{2,6}]-undec-4-ene (14) and (5α,7,7,11β-Tetramethyl-8βH-tetracyclo[6.3.0.0^{1,5}0^{4,6}]undec-2-ene. (Cyclosilphinene, 15). A solution of arene **13** (3.00 g, 14.85 mmol) in freshly distilled pentane (2 L) was irradiated in a quartz photochemical reactor (3 L) with UV light from a 450-W Hanovia source without a filter for 4 h at room temperature under constant N_2 purging.[24] The resulting yellow solution was concentrated to a yellow oil. The above procedure was performed 20 times. The combined liquid was subjected to column chromatography on a 400 g of silica gel with pentane as an eluant to give 51 g of a 1:1 mixture of **14** and **15** as determined by ^1H NMR analysis. Further purification of a 2.0-g portion by flash chromatography on $AgNO_3$ impregnated silica gel (15% $AgNO_3$, w/w) using 3% ether in pentane as eluent afforded **14** (810 mg, 41%) and **15** (790 mg, 39%).

For **14**, IR (neat): 3171, 3054, 2959, 1456, 1377, 1362, 909, 744 cm^{-1}. ^1H NMR: δ 0.77 (s, 3 H), 0.84 (d, 3 H, J = 7.1), 0.94 (s, 3 H), 1.26 (s, 3 H), 1.44 (m, 3 H), 1.66 (m, 1 H), 1.81 (m, 1 H), 1.89 (m, 1 H), 1.97 (dd, 1 H, J = 9.3, 4.2), 2.41 (d, 1 H, J = 2.4), 5.47 (dd, 1 H, J = 5.4, 2.4), 5.71 (dd, 1 H, J = 5.4, 2.4). ^{13}C NMR: δ 16.10, 18.83, 23.23, 23.33, 23.76, 33.03, 36.83, 38.66, 47.17, 50.75, 54.51, 54.52, 68.72, 130.23, 131.13. Anal. Calcd for $C_{15}H_{22}$: C, 89.04; H, 10.96. Found: C, 89.20; H, 10.96.

For **15**, IR (neat): 3051, 2950, 1456, 1360, 914, 754, 742 cm^{-1}. ^1H NMR: δ 0.86 (m, 1H), 0.96 (d, 3 H, J = 7.3 Hz), 1.01 (s, 3 H), 1.05 (m. 1H), 1.11 (s, 3 H), 1.31 (s, 3 H,), 1.41 (dd, 1 H, J = 7.3, 2.2 Hz,), 1.50 (dtd, 1H, J = 12.2, 7.3, 1.4), 1.57 (dtd, 1H, J = 12.2, 7.3, 6.4), 1.90 (dd, 1H J = 11.7, 6.4), 2.02 (dtd, 1 H, J = 12.2, 7.3, 1.4), 2.24 (sextet, 1H, J = 7.3), 5.45 (d, 1 H, J = 5.4), 5.65 (dd,1 H, J = 5.4, 2.2). ^{13}C NMR: δ 18.80, 19.63, 28.34, 29.06, 29.62, 33.97, 36.88, 38.20, 41.06, 49.04, 50.12, 70.25, 72.24, 127.76, 135.45. Anal. Calcd for $C_{15}H_{22}$: C, 89.04; H, 10.96. Found: C, 89.55; H, 10.86.

5α,7,7,11β-Tetramethyl-8βH-tricyclo[6.3.0.0^{1,5}]undec-2-ene [(±)-Silphinene, 4]. A solution of **15** (700 mg, 3.47 mmol) in ethylamine (20 mL) was stirred and cooled at −78 °C as small pieces of lithium wire (150 mg, 21.4 mmol, 3.2 mm diameter, 5 mm long) were added. The suspension was stirred

at −78 °C for 7 h, and a deep blue color formed. The excess lithium was removed with a spatula, the blue color was discharged by adding 3-hexyne (ca. 1 mL), and methanol (ca. 5 mL) was added to the yellow solution. The ethylamine was removed by warming to room temperature, and water (50 mL) was added. The aqueous solution was extracted with ether (3 × 50 mL). The combined organic layers were dried ($MgSO_4$) and concentrated at reduced pressure. Chromatography on silica gel (pentane) afforded 531 mg (74%) of a 9:1 mixture of **4** and its 6,7-ene isomer according to GC analysis. This mixture was used without further purification. The IR, ^{1}H, and ^{13}C NMR data for (±)-silphinene **4** are consistent with those in the literature.[4] IR (neat): ν_{max} 3046, 1624, 1456 cm^{-1}. ^{1}H NMR: δ 0.81 (d, 3H, J = 7.2,), 0.92 (s, 3H), 0.97 (s, 3H), 1.07 (s, 3H), 1.64 and 1.67 (ABdd, 2H, J = 14.1), 1.85 (m,1H), 1.99 (m, 1H), 2.16 (dt, 1H, J = 17.1, 2.1), 2.46 (dt, 1H, J = 17.1, 2.1), 5.44 (dt, 1H, J = 2.5, 2.2,), 5.58 (dt, 1H, J = 3.9, 2.0). ^{13}C NMR: δ 16.42, 26.63, 27.39, 27.63, 30.91, 37.40, 38.55, 39.35, 49.20, 50.92, 58.27, 63.68, 72.33, 125.33, 138.39. ^{1}H NMR data for the minor component: δ 0.92 (d, 3H, J = 7), 0.95 (s, 3H), 1.01 (s, 3H), 1.10 (s, 3H), 5.46 (m, 1H), 5.49 (br s, 1H). Anal. Calcd for $C_{15}H_{24}$: C, 89.04; H, 10.96. Found: C, 89.20; H, 10.96.

Silphinene Epoxides (17α and 17*β*). A solution of the 9:1 mixture of (±)-silphinene (**4**) and its 6,7-ene isomer (530 mg, 2.41 mmol) in CH_2Cl_2 (80 mL) was stirred and cooled at 0 °C as *m*-chloroperoxybenzoic acid (2 g, 55%, 11.6 mmol) was added in portions. The solution was warmed to room temperature, stirred for 2 h, diluted with CH_2Cl_2 (100 mL), washed with aqueous Na_2CO_3 (10%, 3 × 100 mL) and brine, and dried ($MgSO_4$). Concentration by rotary evaporation and purification by column chromatography (20:1 hexane/ether) afforded a 3:1 mixture of **17α** and **17*β*** (313 mg, 54%) of the known epoxides.[4a,24a] This mixture was subjected to $LiAlH_4$ reduction without further purification. A small amount of each epoxide was separated for spectral characterization by a second flash chromatography. The following spectral data agree with the literature data[4a] except that the opposite relative stereochemistry was assigned. For **17α**, ^{1}H NMR (300 MHz): δ 0.91 (s, 3H), 1.00 (s, 3H), 1.05 (s, 3H), 1.16 (d, 3H J = 6.9), 2.10 (d, 1H, J = 2.1), 3.38 (d, 1H, J = 2.1), 3.46 (d, 1H, J = 2.1). For **17*β***, ^{1}H NMR (300 MHz): δ 0.95, 0.96, 0.97, 1.08 (4s, 12H, 4CH_3), 1.90 (d, 1H, J = 12.6), 2.00 (m, 1H), 2.09 (m, 1H), 2.56 (t, 1H, J = 8.9), 3.03 (t, 1H, J = 8.9), 3.30 (d, 1H, J = 2.5), 3.57 (t, J = 2.1). ^{13}C NMR (75 MHz): δ 14.17, 24.84, 26.43, 22.71, 32.22, 38.56, 38.63, 40.09, 45.12, 49.16, 58.63, 61.53, 62.18, 65.04, 44.24. MS (EI, 70 eV) *m*/*z* (relative intensity): 222 (M$^+$, 2.2), 177 (100).

2α,7,7,11*β*-Tetramethyl-6α,8*β*H-tricyclo[6.3.0.0^{1,3}]undecane (16). The reduction of **14** (404 mg, 2 mmol) with lithium in ethylamine was carried out at −78 °C for 2 h as described for the reduction cyclosilphinene to silphinene (**4**). Flash chromatography on silica gel with pentane as eluant afforded **16** (390 mg, 96%, 91% pure by GC). Further purification was carried out by a second chromatography on $AgNO_3$-impregnated silica (15%, w/w) with pentane as an eluant to give pure **16** (350 mg, 86%) and a 1:1 mixture of **4** and its 6,7-ene isomer (15 mg, 3%). For **16**, IR (neat): ν_{max} 2905, 1451, 1360, 810 cm^{-1}. ^{1}H NMR: δ 0.75 (s, 3H, CH_3,H-9), 0.78 (d, 3H, J = 7.1), 0.88 (s, 3H), 1.24 (s, 3H), 1.26 (m, 2H), 1.50 (m, 4H), 1.69 (m, 4H), 1.83 (m, 3H), 1.96 (m, 1H). ^{13}C NMR: δ 16.16, 18.61, 22.37, 24.20, 24.35, 25.14, 26.62, 32.44, 33.39, 37.14, 42.45, 48.47, 51.06, 51.54, 64.01. MS (EI, 70 eV) *m*/*z* (relative intensity): 206 (M$^+$, 1.6), 191 (100.0), 109 (60.0). Anal. Calcd for $C_{15}H_{26}$: C, 87.30; H, 12.70. Found: C, 87.28; H, 12.70.

5α,7,7,11*β*-Tetramethyl-8*β*H-tricyclo[6.3.0.0^{1,5}]undecan-2α- and 2*β*-ols (Silphin-1α- and 1*β*-ols, 18α-OH and 18*β*-OH). Method A: Reduction of Silphinene Epoxides. A suspension of $LiAlH_4$ (1 g, 26.3 mmol) in THF (25 mL) was stirred and cooled at 0 °C as a 3:1 mixture of **17α** and **17*β*** (300 mg, 0.15 mmol) in THF (5 mL) was added. The reaction mixture was then heated at reflux temperature for 4 h and cooled to room temperature. The excess hydride was destroyed by adding water (1 mL) and 15% aqueous NaOH (1 mL), and the white salts were separated by filtration. The THF was removed under vacuum and the product was dissolved in ether (50 mL). The ethereal solution was washed with brine and dried ($MgSO_4$). After evaporation of solvent, the crude oil was purified by column chromatography (6:1 hexane/ether) to give **18α**-OH (170 mg, 0.77 mmol, 57%) and **18*β***-OH (60 mg, 0.27 mmol, 21%) as crystalline solids. The ^{1}H and ^{13}C NMR data agree with the literature data except that the opposite stereochemistry was assigned to the isomers.[4a] The stereochemistry of **18α**-OH was established by a single crystal X-ray crystallographic analysis.

For **18α**-OH, mp: 51−52.5 °C (recrystallization from hexane). IR (neat): ν_{max} 3487 (OH), 2950, 2870, 1458, 1385, 785 cm^{-1}. ^{1}H NMR: δ 0.92 (s, 3H), 0.96 (s, 3H), 1.22 (s, 3H), 1.25 (d, 3H, J = 7.0, CH_3, H-15), 1.61 (m, 2H), 1.71−1.84 (m, 2 H), 2.00 (m, 1H), 2.13 (m, 1H), 4.14 (m, 1H). ^{13}C NMR: δ 18.07, 24.13, 27.39, 27.47, 32.12, 32.88, 37.34, 38.90, 39.94, 40.62, 49.28, 60.33, 63.30, 70.38, 82.30. Anal. Calcd for $C_{15}H_{26}O$: C, 81.08; H, 11.71. Found: C, 81.06; H, 11.70.

For **18*β***-OH, mp: 63−65 °C (recrystallization from hexane). IR (neat): ν_{max} 3407 (OH), 2953, 2870, 1464, 1379, 1061, 785 cm^{-1}. ^{1}H NMR: δ 0.94 (s, 3H), 0.96 (s, 3H), 0.99 (s, 3H), 1.07 (d, 3H, J = 6.6, CH_3, H-15), 1.13 (td, 1 H, J = 12.7, 6.1), 1.25 (m, 2 H), 1.42 (dd, 1 H, J = 12.6, 6.7), 1.46−1.63 (m, 3 H), 1.54 and 1.59 (AB dd, 2H, J = 13.1), 1.77 (m, 1 H), 1.96 (m, 1 H), 2.15 (m, 1 H), 2.32 (dd, 1 H, J = 9.5, 3.9), 4.15 (dd, 1 H, J = 11.1, 6.1). ^{13}C NMR: δ 17.03, 23.66, 26.03, 26.27, 30.51, 31.22, 37.23, 38.33, 38.50, 40.05, 48.67, 58.01, 60.52, 66.89, 75.60. MS (EI, 70 eV) *m*/*z* (relative intensity): 222 (M$^+$, 1.6), 204 (8.8), 163 (100.0), 148 (20.7), 109 (20.9), 107 (20.8). Anal. Calcd for $C_{15}H_{26}O$: C, 81.08; H, 11.71. Found: C, 80.95; H, 11.82.

Method B: Reduction of Silphin-1-one. A suspension of $LiAlH_4$ (10 g, 26.3 mmol) in THF (125 mL) was stirred and cooled at 0 °C as silphin-1-one (**19**) (1.10 g, 5 mmol) in THF (5 mL) was added. The reaction mixture was then heated at reflux temperature for 4 h, and cooled to room temperature. The excess hydride was destroyed by addition of water (5 mL) and 15% aqueous NaOH (10 mL), and the white salts were filtered. The filtrate was diluted with ether (250 mL), and the THF solution was washed with saturated NaCl and concentrated under reduced presure. Purification by flash chromatography on silica gel (6:1 hexane/ether) gave 144 mg (13%) of silphinan-1α-ol (**18α**-OH) and 877 mg (79%) of silphinan-1*β*-ol (**18*β***-OH) as crystalline solids. The physical and spectral properties of the products were identical to those given above.

Method C: Large-Scale Preparation from 14 + 15 Mixture. A 1:1 mixture of vinylcyclopropanes **14** and **15** (10.0 g, 49.5 mmol) in ethylamine (250 mL) was reduced with lithium wire (4.0 g, 576 mmol) at −78 °C for 4 h, as described above for pure **15**. The excess lithium was destroyed and the product was isolated in the same manner. The resulting crude yellow oil (9.84 g, 97%) containing **4** and its 7-ene isomer (9:1 ratio), and **16** was used without purification.

The three-component mixture (9.8 g, 48.0 mmol) in CH_2Cl_2 (280 mL) was epoxidized with *m*-chloroperoxybenzoic acid (18.1 g, 55%, 57.6 mmol) as described for **4** above. The reaction was followed by TLC. After 4 h, the CH_2Cl_2 solution was washed with Na_2CO_3 (10%, 3 × 100 mL) and brine, dried ($MgSO_4$), and evaporated at reduced pressure. Purification of the remaining crude oil by column chromatography (20:1 hexane: ether) gave saturated hydrocarbon **16** (5.9 g) and a mixture of epoxides **17α** and **17*β*** (3.8 g, 3:1 ratio).

A 3:1 mixture of crude epoxides **17α** and **17*β*** (3.6 g, 16.4 mmol) in THF (150 mL) was reduced with $LiAlH_4$ (9.32 g, 245 mmol) in THF (150 mL) as described previously. After 4 h, the excess hydride was destroyed and the product was isolated by extraction according to the previous procedure. Purification by flash chromatography with 6:1 hexanes/ether as eluent afforded 1.31 g (36%, from epoxide **17α**) of silphin-1α-ol (**18α**-OH), mp 51−53 °C, and 0.74 g (21% from epoxide **17*β***) of silphin-1*β*-ol (**18*β***-OH), mp 61−63 °C. The purity of each isomer was more than 95%. The identity of the products was

established by comparison of ^{1}H NMR spectra with those of the pure isomers above.

5α,7,7,11β-Tetramethyl-8βH-tricyclo[6.3.0.0^{1,5}]undecan-2-one (Silphin-1-one, 19). A solution of 752 mg (3.39 mmol) of silphin-1α-ol (**18**α-OH), tetrapropylammonium perruthenate (60 mg, 0.17 mmol), and 4-methylmorpholine *N*-oxide (688 mg, 5.08 mmol), in CH_2Cl_2 (7 mL) containing 4 Å molecular sieves (1.69 g) was stirred at room temperature under N_2 for 12 h.[25] The reaction progress was followed by TLC. The solution was filtered through a pad of silica gel (10 g) with CH_2Cl_2 (50 mL). Concentration under reduced pressure and purification by flash chromatography (6:1 hexane:ether) gave 726 mg (97%) of silphin-1-one (**19**) as a colorless oil. IR (neat) ν_{max}: 2952, 2869, 1725, 1678, 1460, 1113 cm^{-1}. ^{1}H NMR: δ 0.89 (d, 3H, J = 6.8, CH_3), 0.95 (s, 3H), 0.98 (s, 3H), 1.19 (s, 3H), 1.39 (m, 1 H), 1.63 (m, 3H), 1.68 and 1.73 (ABdd, 2H, J = 13.2), 1.88 (m, 2 H), 2.12 (m, 1 H), 2.25 (m, 1 H), 2.36 (m, 1 H). ^{13}C NMR: δ 15.54, 25.97, 27.27, 27.61, 32.41, 34.65, 37.28, 37.94, 39.44, 39.78, 49.14, 57.50, 64.84, 72.50, 224.40. MS (EI, 70 eV) *m*/*e* (relative intensity): 220 (M$^+$, 9.3), 205 (14.8), 165 (100.0), 149 (19.0), 107 (29.6). Anal. Calcd for $C_{15}H_{24}O$: C, 81.82; H, 10.91. Found: C, 81.89; H, 11.10.

Silphinan-1-one (**19**) was also prepared from silphinan-1β-ol (222 mg) in the same manner: yield, 199 mg (90%). The spectral properties of the product were identical to those given above.

Silphin-1α-yl Methanesulfonate (18α-OMs). A solution of silphinan-1α-ol (100 mg, 0.45 mmol) in 1 mL of pyridine-d_5 was stirred and cooled at 0 °C as CH_3SO_2Cl (103 mg, 0.90 mmol) was added via syringe. The solution was allowed to warm to room temperature, stirred for 3 h, and diluted with 10 mL of pentane. The pentane solution was washed one time each with water, 2 N HCl, and saturated Na_2CO_3; dried ($MgSO_4$); and concentrated to give **18**α-OMs as an unstable yellow oil. ^{1}H NMR 400 MHz (pyridine-d_5): δ 0.83 (3H, s), 0.85 (3H, s), 1.14 (3H, s), 1.27 (3H, d, J = 7.1), 3.24 (3H, s), 5.07 (1H, dd, J = 3.2, 3.4).

Silphin-1β-yl Methanesulfonate (18β-OMs). The mesylation of **18β**-OH (100 mg, 0.45 mmol) with CH_3SO_2Cl (103 mg, 70 μL, 0.90 mmol) in pyridine (100 μL) was carried out for 2 h at room temperature, and the product was isolated as described above for **18**α-OMs. The crude product (133 mg, 99%) was sufficiently pure (95% by ^{1}H NMR) and was used for solvolysis without purification. A small sample (16 mg) was purified for characterization by chromatography on silica gel (6:1 hexanes−ether). IR (neat): ν_{max}2950, 1455, 1357, 1177, 890 cm^{-1}. ^{1}H NMR (pyridine-d_5): δ 0.84 (s, 3H), 0.85 (s, 3H), 0.97 (s, 3H), 1.00 (m, 1H), 1.03 (d, 3H, J = 6.7), 1.38 (m, 2H), 1.43 and 1.48 (ABdd, 2H, J = 12.8), 1.68 (m, 2H), 1.84 (m, 2H), 2.06 (m, 2H), 2.43 (dd, 1H, J = 9.2, 4.3), 3.25 (s, 3H), 5.68 (dd, 1H, J = 10.4, 6.1). ^{13}C NMR (pyridine-d_5): δ 25.81, 25.84, 25.87, 38.11, 38.15, 38.47, 38.86, 38.89, 38.96, 40.16, 47.85, 59.50, 59.73, 60.22, 67.18, 84.02.

Silphin-1α-yl Trifluoroacetate (18α-O_2CCF_3). A solution of silphinan-1α-ol (**18**α-OH, 10 mg, 0.045 mmol) and 4-(dimethylamino)pyridine (5 mg, 0.41 mmol) in 200 μL of pyridine was stirred as trifluoroacetic anhydride (27 mg) was added. The reaction mixture was stirred for 1 h at room temperature after which it was diluted with ether and washed with 2 N HCl and saturated $NaHCO_3$. The organic layer was dried ($MgSO_4$) and concentrated to afford 10 mg (83%) of **18**α-O_2CCF_3. ^{1}H NMR: δ 0.90 (s, 3H), 0.94 (s, 3H), 1.03 (d, 3H, J = 7.1), 1.19 (s, 3H), 1.34−1.85 (m, 10H), 1.98 (s, 3H), 1.97−2.10 (m, 2H), 5.07 (dd, 1H, J = 3.9, 1.7).

(1*S,6*R**)-1,2,3,4,5,6-Hexahydro-1,3,3,6-tetramethylpentalen-1-propanal (Secosilphinal, 20).** This procedure was based on a literature method.[30] A solution of silphin-1α-ol (**18**α-OH, 222 mg, 1.0 mmol) in CH_3CN (10 mL) was stirred at room temperature as ceric ammonium nitrate (2.2 g, 4 mmol) in H_2O (40 mL) was added in one portion. The mixture was allowed to stir at room temperature for 5 min, and the reaction progress was monitored by TLC. The mixture was poured into ice water (250 mL), and the aqueous layer was extracted with ether (3 × 100 mL). The combined organic layers were washed with water (100 mL) and brine (50 mL) and dried ($MgSO_4$). Evaporation of the solvent followed by chromatography, using hexanes/ether (95:5) as eluant afforded bicyclic enal **20** (56 mg, 51%), unreacted silphin-1α-ol (30 mg, 14%), and a mixture of enal **20** and silphin-1α-ol (ratio of 1:1, 64 mg, 29%). The yield decreased with higher conversions. Attempts to improve the yield by changes in amounts and concentrations were unfruitful.

For **20**, IR (neat): ν_{max} 2952, 1726, 1456, 1371, 1358, 1188, 808 cm^{-1}. ^{1}H NMR: δ 0.88 (m, 1H), 1.026 (d, 3H, J = 6.8), 1.03 (s, 3H), 1.04 (s, 3H), 1.09 (s, 3H), 1.26 (m, 1H), 1.70 (m, 2 H), 1.78 and 1.92 (ABdd, 2H, J = 13.4), 2.00 (m, 1H), 2.06 (m, 1H), 2.41 (m, 1H), 2.62 (m, 1H), 9.80 (t, 1H, J = 2.0). ^{13}C NMR: δ 20.34, 24.47, 27.56, 28.66, 29.05, 32.82, 35.48, 37.74, 39.53, 31.08, 44.28, 56.88, 150.79, 153.32, 203.15. MS (EI, 70 eV) m/e (relative intensity): 220 (M$^+$, 10.2), 205 (10.36), 163 (100.0). Anal. Calcd for $C_{15}H_{22}$: C, 81.76; H, 10.98. Found: C, 82.05; H, 11.69.

(1*S,6*R**)-1,2,3,4,5,6-Hexahydro-1,3,3,6-tetramethylpentalen-1-propanol (Secosilphinol 21).** A solution of **20** (190 mg, 0.86 mmol) in dry ether (12 mL) was added to a stirred solution of 330 mg (8.6 mmol) of $LiAlH_4$ in 10 mL of ether at 0 °C. After 5 min ether (25 mL) and water (0.5 mL) were added, the salts were filtered, and the ethereal filtrate was washed with water (25 mL). The aqueous layer was extracted with ether (2 × 25 mL). The combined organic layers were washed with 10% HCl (10 mL), 5% Na_2CO_3 (10 mL), and brine (5 mL) and dried ($MgSO_4$). Removal of the solvent, and purification by chromatography using hexane as eluant furnished 181 mg (94%) of **21** as a colorless oil. IR (neat): ν_{max} 3326 (OH), 2862, 1456, 1057, 735, 908 cm^{-1}. ^{1}H NMR: δ 1.02 (s, 3H), 1.03 (d, 3H, J = 6.8 Hz), 1.04 (s, 3H), 1.06 (s, 3H, CH_3), 1.41 (m, 2 H), 1.51 (m, 1H), 1.64 (m, 3H), 1.74 and 2.01 (ABdd, 2H, J = 13.2), 1.98 (m, 1H), 2.05 (m, 1H), 2.37 (m, 1H), 2.61 (m, 1H), 3.64 (m, 1H). ^{13}C NMR: δ 20.40, 24.45, 27.57, 28.69, 29.09 (2C?), 35.57, 37.42, 37.79, 39.45, 44.50, 57.06, 63.81, 151.73, 152.17. Anal. Calcd for $C_{15}H_{22}$: C, 81.08; H, 11.71. Found: C, 81.09; H, 11.79.

Secosilphinyl *p*-Nitrobenzenesulfonate (21-ONs). The procedure was modeled after the preparation campholenyl nosylate.[30] A solution of **21** (111 mg, 0.50 mmol) in pyridine (15 mL) was stirred at room temperature as *p*-nitrobenzenesulfonyl chloride (1.22 g, 5.5 mmol) was added in one portion. The solution was allowed to stir at room temperature for 2 h, the solution was poured into ice water (50 mL), and the aqueous layer was extracted with ether (3 × 50 mL). The combined organic layers were washed with 10 mL of water and 10 mL of brine and dried ($MgSO_4$). Evaporation of solvent followed by flash chromatography using 6:1 hexanes−ether as eluant gave the nosylate (**21**, X = ONs, 151 mg, 77%) as a yellow oil. The neat nosylate slowly decomposed when stored at −20 °C. ^{1}H NMR (pyridine-d_5): δ 0.94 (d, 3 H, J = 6.7), 0.99 (s, 3H), 1.00 (s, 3H), 1.02 (s, 3H), 1.34 (m, 1 H), 1.39 (m, 2H), 1.63 (m, 3H), 1.87 and 1.89 (ABdd, 2H, J = 13.4), 1.97 (m, 1 H), 2.40 (m, 1H), 2.59 (m, 1H), 4.13 (t, 2H, J = 7.1), 8.11 (d. 2H, J = 9.0), 8.42 (d, 2H, J = 9.0).

Kinetic Measurements for Silphinyl Mesylates. The rates for **18β**-OMs in Table 1 were determined by placing the mesylate (0.22 mg, 0.10 mmol) and 1.0 mL of 3:1 acetone-d_6/D_2O in a sealable NMR tube under N_2 with TMS and benzene as internal standards. After sealing the tube, the solution was placed in an oil bath maintained at either 70 or 110 °C. At regular intervals, the NMR tube was quickly cooled to 0 °C, and ^{1}H NMR spectra were recorded at 25.0 ± 0.2 °C in a thermostated probe. The disappearance of starting mesylate (H-1 integration for the internal standards) was monitored as a function of time by comparison with the peaks for the internal standards. The rate measurements were taken over 5 half-lives. Data were fit to the first-order rate expression. The rate constants are the average of the disappearance of starting material and the formation of the products. The solvolysis rate of **18**α-OMs was measured similarly in the thermostated probe at 25.0 ± 0.2 °C.

Preparative Solvolyses of Silphin-1α-yl Mesylate (18α-OMs). A. Formolysis. A solution of **18**α-OMs prepared from silphinan-1α-ol (100 mg, 0.45 mmol) in 3 mL of 96% formic

acid buffered with HCO_2Na (43 mg, 0.94 mmol) was stirred at room temperature for 15 min after which 50 mL of pentane was added. The pentane solution was washed with water, 2 N HCl, and saturated Na_2CO_3; dried ($MgSO_4$); and concentrated to give a colorless oil. GC analysis of the crude products showed an 8:1 mixture of α-terrecyclene and silphinene (94%), three unidentified minor olefins (3%), silphin-1α-ol (1.5%), and formate ester (1.5%). Flash chromatography of the crude mixture using pentane as eluent afforded 75 mg (81%) of an 8:1 mixture of α-terrecyclene (**5**) and silphinene (**4**) as a colorless oil.

For α-terrecyclene (**5**), ^{1}H NMR: δ 0.82 (d, 3H, J = 6.8), 1.06 (s, 3H), 1.14 (3s, H), 1.14−1.19 (m, 1H), 1.40 (d, 1H, J = 13.3), 1.40−1.49 (m, 1H), 1.51 (d, 1H, J = 13.3), 1.57 (bs, 3H), 1.54−1.63 (m, 1H), 1.74 (dd, 1H, J = 2.9, 3.2), 1.87 (app septet, 1H, J = 6.6), 1.97 (app quintet, 1H, J = 6.8), 2.24−2.32 (m, 2H), 2.43−2.52 (m, 1H), 5.10 (bs, 1H). ^{13}C NMR: δ 13.68, 17.49, 26.23, 27.01, 28.83, 34.18, 35.78, 35.85, 40.93, 49.44, 51.64, 53.69, 63.50, 122.45, 146.74. Anal. Calcd for $C_{15}H_{24}$: C, 88.16; H, 11.84. Found: C, 88.15; H, 11.82.

B. Aqueous Solvolysis. A solution of **18**α-OMs prepared from silpinan-1α-ol (100 mg, 0.45 mmol) as described above, pyridine (53 mg, 0.68 mmol) in 4 mL of 3:1 acetone/water was stirred at room temperature, and the progress of the reaction was followed by TLC (6:1 hexane: ether). After 30 min the reaction mixture was diluted with 50 mL of pentane. The pentane solution was washed with water, 2 N HCl, and saturated Na_2CO_3; dried ($MgSO_4$); and concentrated to give a yellow oil. Flash chromatography with pentane/ether (8:1) as the eluant afforded 62 mg (66%) of a 63:37 mixture (94% GC purity) of α-terrecyclene (**5**) and silphinene (**4**), 3 mg (3%) of recovered **18**α-OH, and 13 mg (13%) of 2,2,4,9-trimethyltricyclo-[5.4.0.0.^{4,8}]undecan-8-ol (**22**). The presence of isocomene and modhephene (ca. 0.4%) in the olefin fraction was established by GC co-injection with authentic samples and GC/MS comparison with their authentic mass spectra. Small amounts (less than 1%) of at least four unknown olefins were also present in the olefin fraction. Flash chromatography on 15% $AgNO_3$ silica gel with pentane as the eluant gave α-terrecyclene (**5**) (33 mg, 36%) and silphinene (**4**) (22 mg, 24%). TPAP/NMO oxidation[25] of **18**α-OH afforded ketone **19** (2 mg, 67%).

For **22**, IR (neat): ν_{max} 3617, 3503, 2955, 1479, 1455, 1342, 1061 cm^{-1}. ^{1}H NMR: δ 0.89 (s, 3H), 0.91 (s, 3H), 1.13 (d, 3H, J = 7.2, CH_3), 1.19 (s, 3H, CH_3), 1.33 (m, 3 h), 1.50 (m, 3 H), 1.60 (m, 2 H), 1.65 (m, 2 H), 1.73 (m, 2 H), 1.88 (m, 2 H), 1.97 (dd, 1 H, J = 7.1, 3.7), 2.03 (dd, 1 H, J = 13.9, 6.8). ^{13}C NMR: δ 19.06, 20.42, 25.24, 25.34, 29.81, 30.68, 30.93, 32.02, 34.32, 36.11, 46.16, 46.26, 46.70, 52.31, 81.65; FI/MS m/z 222 (M_t); Anal. Calcd for $C_{15}H_{26}O$: C, 81.08; H, 11.71. Found: C, 81.10; H, 11.68.

C. Acetolysis. A solution of **18**α-OMs prepared from silpinan-1α-ol (100 mg, 0.45 mmol) as described above in 2 mL of anhydrous acetic acid buffered with 60 mg (0.73 mmol) of sodium acetate was stirred for 1 h at room temperature. The solvolysis was stopped by diluting with 10 mL of pentane. The pentane solution was washed with 10 mL of water and 10 mL of saturated $NaHCO_3$; dried ($MgSO_4$); and concentrated to give a yellow oil. Flash chromatography with pentane as eluant gave 56 mg (60%) of a 65:35 mixture of olefins **5** and **4**. Further elution with 6:1 hexanes/ether afforded 5 mg (4%) of a 3:1 mixture of the acetate of **22** and **18**α-O_2CCH_3. The identity of silphinan-1α-yl acetate (**18**α-O_2CCH_3) was confirmed by GC co-injection. The structure of the acetate of **22** was determined by reduction of the acetate mixture with $LiAlH_4$ and subsequent co-injection with **22.**

Aqueous Solvolysis of Silphin-1*β*-yl Mesylate (18-OMs). A solution of freshly prepared mesylate (130 mg, 0.43 mmol) and 300 μL (3.7 mmol) of pyridine in 4 mL of 3:1 acetone/water (v/v) in a 10-mL resealable pressure tube (Aldrich Chemical Co.) under nitrogen was stirred and heated at 70 °C for 14 h. The progress of the solvolysis was followed by TLC. The pressure tube was cooled to room temperature, and the solution was concentrated under reduced pressure to remove most of the acetone. The products were extracted into CH_2Cl_2 (3 × 10 mL). The combined CH_2Cl_2 extracts were washed with 2 M HCl (1 mL), 10% Na_2CO_3 (1 mL), and brine (1 mL) before drying ($MgSO_4$). Removal of solvent afforded a colorless oil. The products were separated into three main fractions by flash chromatography on silica gel with pentane as eluant. The olefin fraction (70 mg, 79%) was a 4:3 mixture of α-terrecyclene (**9**) and silphinene (**6**), according to GC analysis with authentic samples. Co-injection and GC analyses and GC/MS comparisons with authentic isocomene and modhephene demonstrated the presence of the sesquiterpenes at the level of ca. 0.4%. Chromatography on 15% $AgNO_3$-impregnated silica gel with pentane as eluant gave 29 mg of silphinene (33%) and 35 mg of α-terrecyclene (40%), the ^{1}H and ^{13}C NMR spectra of which are identical to those above.

The second fraction (1.5 mg, 2%) contained silphin-1α-ol, which was identified by ^{1}H NMR spectroscopy, and the third fraction (16 mg, 17%) contained tertiary alcohol **22**-OH. Since silphin-1α-ol and presilphiperfolanol (**23**) had the same TLC R_f value and capillary GC retention time, the second fraction was subjected to oxidation with tetrapropylammonium perruthenate (28 mg, 0.08 mmol) in 2 mL of CH_2Cl_2. After 24 h, the mixture was diluted with CH_2Cl_2 (2 mL) and passed through a pad of silica gel with ether (25 mL) as eluent. Evaporation of solvent afforded a yellow oil which was purified by flash chromatography (6:1 hexane/ether) to give silphin-1-one (**19**, 1 mg, 68%). The IR, ^{1}H NMR, and ^{13}C NMR spectra for **18**α-OH, **19**, and **22** correspond to those reported above. The amount of **23** present, if any, in fraction 2 before or after TPAP oxidation was estimated to be <0.5%.

(±)-Isocomene.[28] Wittig methylenation of the tricyclic ketone precursor (223 mg) followed by rearrangement with *p*-TsOH in benzene afforded 120 mg of (±)-isocomene (purity >99% by GC) after purification by flash chromatography of silica gel. The ^{1}H NMR, ^{13}C NMR, and MS data corresponded well with the literature.[28]

(±)-Modhephene.[29] The sample was purified by chromatography on silica gel (hexane) to a final purity of ca. 90%. The ^{1}H NMR, ^{13}C NMR, and MS data corresponded well with the literature data.[1b,2]

Acetolysis of Nosylate 21 (X = ONs). The procedure was similar to one reported for solvolytic cyclization of campholenyl nosylate.[30] A solution of nosylate **21** (X = ONs, 102 mg, 0.25 mmol) and anhydrous sodium acetate (30 mg, 0.6 mmol) in dry acetic acid (15 mL) was stirred and heated at 60 °C for 5 h. The cooled solution was poured into ice water (50 mL), and the products were extracted with ether (3 × 50 mL). The combined organic layers were washed with 10% Na_2CO_3 (25 mL) and dried ($MgSO_4$). Evaporation of the solvent followed by flash chromatography on silica gel with 9:1 hexanes/ether as eluant gave 3 mg (6%) of a 2:1 mixture of two olefins according to GC analyses and 52 mg (78%) of its acetate as a colorless oil. The major and minor olefins were initially identified by co-injection GC and GC/MS comparisons with authentic samples. Separation of isocomene (~0.7 mg, 85% purity by GC) and modhephene (~0.5 mg, 79% purity by GC) was accomplished by flash chromatography on 1 g of 20% $AgNO_3$/silica gel (6 mm diameter, 0.5 mL fractions) with pentane as eluant. The ^{1}H NMR spectra, GC retention times, and GC/MS of the separated olefins were identical to those of the reference standards.[28,29]

For **21**-OAc, ^{1}H NMR: δ 1.02 (d, 3H, J = 6.9, CH_3), 1.023 (s, 3H, CH_3), 1.04 (s, 3H, CH_3), 1.06 (s, 3H, CH_3), 1.25 (s, 1H), 1.40 (m, 2H), 1.55−1.75 (m, 4H), 1.95 (m, 2H), 2.04 (s, 3H, CH_3), 2.47 (m, 1H), 2.67 (m, 1H), 4.02 (m, 2H). ^{13}C NMR: δ 20.28, 21.04, 24.47, 24.99, 27.68, 28.67, 29.11, 35.56, 37.41, 37.76, 39.47, 44.49, 56.93, 65.26, 152.43, 152.41, 171.29. HREIMS calcd for $C_{17}H_{28}O_2$: 264.2989. Found: 264.2988.

1,4,4,11-Tetramethyl-3-chloro[5.3.1.0^{3,8}]undecane (24). A. $TiCl_4$ Rearrangement of Trifluoroacetate, 18α-O_2CCF_3. A solution of silphinyl trifluoroacetate (40 mg, 0.13 mmol) and 2,6-di-*tert*-butylpyridine (26.4 mg, 1.3 mmol) in CH_2Cl_2 (1.5 mL) was stirred under N_2 and cooled at −78 °C, as $TiCl_4$ (414 μL of 1.0 M CH_2Cl_2 solution, 0.4 mmol) was added in one portion. After 1 h, pentane (25 mL) was added, and the solution was washed with 10% HCl (15 mL), 10% $NaHCO_3$ (15 mL), and brine (5 mL) and dried ($MgSO_4$). Evaporation

of solvent under reduced pressure followed by chromatography (pentane) gave 28 mg (93%) of the chloride as a light yellow oil. Efforts were made to detect other intermediates by stopping the reaction when ca. 20% of starting material was still present. No other compounds were found in detectable amount. The same chloride was isolated when 0.5, 1, 3, or 10 equiv of 2,6-di-*tert*-butylpyridine was used as a buffer.

For **24**, IR (neat): ν_{max} 2930, 1350, 1070, 1010, 980 cm^{-1}. ^{1}H NMR δ 0.79 (s, 3H), 0.88 (d, 3H, J = 7), 0.94 (m, 1H), 1.03 (s, 3H), 1.14 (s, 3H), 1.48 (m, 2H), 1.64 (m, 2H), 1.78 (m, 1H), 1.95 (m, 2H), 2.19 (m, 1H). ^{13}C NMR δ 17.57, 22.39, 23.54, 25.01, 25.42, 25.55, 26.57, 32.91, 33.94, 37.39, 39.31, 40.42, 44.76, 50.58, 83.64. MS (EI, 70 eV) *m*/*z* (relative intensity): 204 (M^+, 24), 189 (100), 161 (21), 147 (24), 133 (16), 119 (22), 105 (14), 91 (13).

B. From Alcohol 25. A solution of **25** was stirred at room temperature as $SOCl_2$ (8 mg, 0.10 mmol) was added in one portion. The mixture was allowed to stir at room temperature for 30 min. The mixture was poured into ice water (15 mL) and the aqueous solution was extracted with CH_2Cl_2 (3 × 10 mL) The combined organic layers were washed with 10% Na_2CO_3 (2 × 10 mL) and dried ($MgSO_4$). Evaporation of the solvent yielded 10 mg (83%) of a yellow oil. GC and ^{1}H NMR spectra showed chloride **24** was the only product.

1,4,4,11-Tetramethyl[5.3.1.0^{3,8}]undecan-3-ol (25). A solution of 28 mg (0.116 mmol) of chloride **24** (X = Cl) and 20 μL of pyridine in 4 mL of 3:1 acetone/water was placed in a 10-mL resealable pressure tube (Aldrich Chemical Co.) under nitrogen. The solution was stirred and heated at 70 °C for 4 h. The pressure tube was cooled to room temperature, and the solution was concentrated under reduced pressure to remove most of the acetone. The product was extracted into pentane (3 × 20 mL). The combined pentane extracts were washed with 10% HCl (10 mL) and 10% $NaHCO_3$ (10 mL) and dried ($MgSO_4$). Both TLC and GC indicated that only one compound was formed. Removal of solvent followed by chromatography on silica gel with 9:1 hexanes/ether as an eluant afforded 17 mg (66%) **25** as white prisms, one of which was used for X-ray analysis: mp 59−61 °C. IR (neat): ν_{max} 3410, 2910, 1271, 1100, 978 cm^{-1}. ^{1}H NMR: δ 0.76 (s, 3H), 0.85 (s, 3H), 0.86 (s, 3H), 0.94 (s, 3H), 0.99 (m, 1H), 1.11 (m, 5H), 1.38 (m, 6H), 1.92 (m, 1H). ^{13}C NMR: δ 17.60, 20.41, 20.96, 23.21, 25.84, 25.98, 26.80, 32.52, 34.38, 35.28, 38.07, 39.37, 44.02, 48.83, 75.65. Anal. Calcd for $C_{15}H_{26}O$: C, 81.28; H, 11.71. Found: C, 80.89; H, 11.73.

Terrecyclan-2α,3α-diol (26). A solution of **5** (46 mg, 0.225 mmol) in 3 mL of pyridine was stirred as a solution of OsO_4 in pyridine (1.1 mL, 97 mg/mL, 104 mg) was added. After 5 h in the dark 5 mL of 0.68 M $NaHSO_3$ was added. The resulting solution was then stirred overnight, diluted with 20 mL of ether, and washed with 20 mL of 2 N HCl. The ether layer was dried ($MgSO_4$) and concentrated to afford a yellow oil. Flash chromatography using 3:1 (hexanes/ethyl acetate) as eluant gave 20 mg (37%) of diol **26** as colorless crystals. ^{1}H NMR: δ 1.05 (s, 3H), 1.11 (s, 3H), 1.15 (s, 3H), 1.23 (d, 3H, J = 7.1), 1.35 (app q, 2H, J = 14.5), 1.42−1.70 (m, 4H), 1.80 (s, 1H), 1.94−2.12 (m, 4H), 2.41 (dd, 1H, J = 3.9, 12.7), 4.10 (q, 1H, J = 7.1, 4.17 (br q, 1H, J = 8.3). ^{13}C NMR: δ 19.68, 20.18, 26.47, 28.19, 29.75, 32.60, 36.54, 36.82, 39.64, 45.10, 51.58, 60.91, 77.43, 82.27.

2αH-Terrecyclan-3α-ol (27). A solution of 75 mg, (0.30 mmol; 83% purity by GC) of **5** in 2 mL of THF was stirred and cooled at 0 °C as 0.55 mL (0.55 mmol) of 1 M BH_3 in THF was added. The solution was allowed to warm to room temperature and stirred for 2.5 h after which 0.3 mL of 2 N NaOH (1:1 MeOH, H_2O) and 1 mL of 30% H_2O_2 were added. The mixture was stirred for an additional 15 min before diluting with 90: 10 hexane/ethyl acetate. The organic layer was washed with H_2O, dried ($MgSO_4$), and concentrated. Flash chromatography with 70:30 hexanes/ethyl acetate as eluant gave 52 mg (76%) of a white crystalline solid (95% purity by GC). Several recrystallizations from hexane (−10 °C) afforded a pure white crystalline solid; mp 92−94 °C. IR: ν_{max} 3285 cm^{-1}. ^{1}H NMR: δ 0.86 (d, 3H, J = 6.8), 0.93 (d, 3H, J = 7.1), 1.04 (s, 3H), 1.07 (s, 3Hs), 1.13−1.19 (m, 1H), 1.18 (d, 1H, J = 13.5), 1.39 (d, 1H, J = 13.5), 1.38−1.46 (m, 1H), 1.51−1.58 (m, 3H), 1.60−1.68 (m, 1H), 1.73 (app quintet, 1H, J = 7.1), 1.89 (app septet, 1H, J = 7.20), 2.11−2.18 (m, 2H), 3.94 (q, 1H, J = 8.4). ^{13}C NMR: δ 10.96, 16.21, 26.64, 26.83, 28.81, 32.67, 36.48, 38.32, 39.54, 45.34, 46.58, 47.84, 50.81, 57.95, 78.96. Anal. Calcd for $C_{15}H_{26}O$: C, 81.02; H, 11.79. Found: C, 80.65; H, 11.60.

2αH-Terrecyclan-3-one (28). The oxidation of alcohol **27** (20 mg, 0.09 mmol), with tetrapropylammonium perruthenate (2 mg, 0.0045 mmol) and *N*-methylmorpholine *N*-oxide (18 mg, 0.135 mmol) in 2.5 mL of CH_2Cl_2 was carried out at room temperature for 0.5 h as described above for silphinone. Filtration over silica gel with CH_2Cl_2 as eluent and concentration afforded 19 mg (96%) of ketone **28** as a colorless oil. The oil crystallized on standing in the freezer: mp 39−41 °C. IR (neat) ν_{max} 1740 cm^{-1}. ^{1}H NMR: δ 0.87 (3d, H, J = 6.8), 1.01 (d, 3H, J = 7.1), 1.06 (s, 3H), 1.11 (s, 3H), 1.23−1.28 (m, 1H), 1.34 and 1.38 (ABdd, 2H, J = 14.6), 1.53−1.68 (m, 2H), 1.73 (t, 1H, J = 3.2), 1.86 (app quintet, 1H, J = 7.1), 2.03 (tt, 1H, J = 13.8, 6.7), 2.30−2.50 (m, 4H). ^{13}C NMR: δ 16.97, 18.11, 26.91, 26.96, 28.26, 34.29, 35.62, 39.14, 40.66, 43.83, 47.67, 49.63, 49.97, 56.85, 220.41. Anal. Calcd for $C_{15}H_{24}O$: C, 81.76; H, 10.98. Found: C, 81.63; H, 10.99.

Terrecyclene-2α,3α-epoxide (29). A solution of **5** (245 mg, 0.900 mmol, 75% purity by GC) containing 10% silphinene in 35 mL of CH_2Cl_2 was stirred and cooled to 0 °C as *m*-CPBA (451 mg, 0.120 mmol, 55% purity) was added. The solution was stirred at room temperature for 2 h washed with 35 mL of saturated Na_2CO_3, dried ($MgSO_4$), and concentrated to afford a yellow oil. Flash chromatography afforded 170 mg (86%) of epoxide **29** as a colorless oil (100% purity by GC). IR (neat): ν_{max} 2926, 2866, 1373, 1086 cm^{-1}. ^{1}H NMR: δ 1.04 (d, 3H, J = 7.1), 1.09 (s, 3H), 1.16 (s, 3H), 1.29 (s, 3H), 1.38 (d, 1H, J = 13.5), 1.36−1.46 (m, 1H), 1.53 (d, 1H, J = 13.5), 1.55−1.61 (m, 1H), 1.67 (t, 1H, J = 13.5), 1.81−2.61 (m, 6H), 3.140 (s, 1H). ^{13}C NMR: δ 14.26, 17.80, 27.23, 27.43, 28.69, 30.89, 35.39, 36.23, 39.91, 45.76, 48.99, 50.21, 58.22, 61.26, 69.03. Anal. Calcd for $C_{15}H_{24}O$: C, 81.76; H, 10.98. Found: C, 81.82; H, 10.99.

Terrecyclan-2α-ol (30). A suspension of $LiAlH_4$ (147 mg, 3.86 mmol) in 5 mL of THF was stirred as terrecyclene epoxide (**29**, 85 mg, 0.39 mmol) was added. The reaction mixture was refluxed for 6 h, cooled to 0 °C, and hydrolyzed with 15% aq NaOH then water. The white salts were filtered and washed with Et_2O. The combined organic layers were dried ($MgSO_4$) and evaporated to afford 58 mg (68%) of terrecyclan-2α-ol (**30**, 98% purity by GC) as a colorless oil. IR (neat): ν_{max} 3355 cm^{-1}. ^{1}H NMR: δ 1.04 (s, 3H), 1.08 (s, 3H), 1.21 (m, 3H), 1.22 (s, 3H), 1.33 (d, 2H, J = 2.4), 1.36−1.49 (m, 3H), 1.53−1.59 (app dt, 1H, J = 14.6 and 3.9), 1.61−1.67 (m, 1H), 1.71 (t, 1H, J = 3.2), 1.90−2.02 (m, 4H), 2.34 (dd, 1H, J = 3.7, 11.0). ^{13}C NMR δ 20.30, 22.13, 26.52, 26.53, 28.49, 30.29, 32.77, 36.65, 39.75, 40.19, 47.61, 52.05, 52.72, 62.63, 84.71. Anal. Calcd for $C_{15}H_{26}O$: C, 81.02; H, 11.79 Found: C, 80.90; H, 11.69.

Dehydration of Terrecyclan-2α-ol (30). A solution of alcohol **30** (29 mg, 0.131 mmol) in 1 mL of benzene and 400 μL of pyridine at 0 °C was stirred as thionyl chloride (19 mg, 0.156 mmol) was added. The solution was stirred for 30 min and poured into ice−water. Extraction with pentane, drying ($MgSO_4$), and concentration afforded an 4:1 mixture of α- and β-terrecyclenes (**5** and **34**) as determined by GC and ^{1}H NMR analyses.

β*-Terrecyclen-3α-ol (31, R = H).** A solution of Et_2NH (272 mg, 3.74 mmol) in 5 mL of ether at 0 °C was stirred as *n*-BuLi (2.54 mL, 1.47 M in hexane) was added. After warming to room temperature a mixture containing 274 mg of epoxide **29** (1.02 mmol, 82% pure by GC) and 12% of epoxides **17α** and ***17β was added. The reaction mixture was then refluxed for 4 h, cooled to room temperature, and washed with 10 mL of 2 N HCl. The organic layer was dried ($MgSO_4$) and concentrated to afford a pale yellow oil. Flash chromatography with (hexane/Et_2O 3:1) as eluant afforded 177 mg (78%) of the allylic alcohol **31** (R = H) as white crystals: mp 60−61 °C. IR (Nujol): ν_{max} 3316 cm^{-1}. ^{1}H NMR: δ 0.93 (d, 3H, J = 7.6), 1.07 (s, 3H), 1.14 (s, 3H), 1.21−1.29 (m, 1H), 1.36 (bs, 1H),

1.42−1.50 (m, 1H), 1.55 (d, 1H, J = 14.1), 1.55−1.60 (m, 1H), 1.63 (d, 1H, J = 14.1), 1.73−1.79 (m, 2H), 1.92−2.08 (m, 3H), 2.35 (dd, 1H, J = 7.6, 11.7), 4.53 (d, 1H, J = 5.6), 4.75 (s, 1H), 5.14 (s, 1H). ^{13}C NMR: δ 17.73, 26.50, 26.89, 27.81, 34.72, 36.85, 37.77, 39.59, 48.89, 49.61, 54.84, 58.99, 76.34, 107.39, 162.09. Anal. Calcd for $C_{15}H_{24}O$: C, 81.76; H, 10.98. Found: C, 81.77; H, 11.00. Recrystallization from hexane at room temperature afforded colorless crystals suitable for X-ray analysis, mp 73−75 °C.

β-Terrecyclen-3α-yl Acetate (31, R = Ac). A solution of allylic alcohol **31** (R = H, 171 mg, 0.78 mmol) and 4-(dimethylamino)pyridine (20 mg, 0.16 mmol) in 2 mL of pyridine was stirred as acetic anhydride (237 mg, 2.33 mmol) was added. The resulting solution was stirred for 1 h, diluted with 10 mL of water, and extracted with 10 mL of (hexane/Et_2O 3:1). The organic layer was then washed with 10 mL of 2 N HCl and 10 mL of saturated Na_2CO_3, dried ($MgSO_4$), and concentrated to afford 162 mg (79%) of allylic acetate **31** (R = Ac) as a colorless oil. IR (neat): ν_{max} 1738 cm^{-1}. ^{1}H NMR: δ 0.89 (d, 3H, J = 7.3), 1.08 (s, 3H), 1.14 (s, 3H), 1.22−1.30 (m, 1H), 1.42−1.51 (m, 1H), 1.59 (d, 1H, J = 14.2), 1.57−1.62 (m, 1H), 1.66 (d, 1H, J = 14.2), 1.76 (dd, 1H, J = 2.9, 3.4), 1.80 (dd, 1H, J = 6.6, 7.1), 1.92−2.22 (m, 2H), 1.99 (s, 3H), 2.06−2.15 (m, 1H), 2.32 (dd, 1H, J = 7.3, 12.2), 4.84 (s, 1H), 5.25 (s, 1H), 5.54 (d, 1H, J = 5.6). ^{13}C NMR: δ 17.47, 21.47, 26.51, 26.88, 27.77, 34.84, 35.76, 37.33, 39.59, 49.24, 49.43, 54.93, 59.00, 78.48, 110.76, 157.41, 170.68. Anal. Calcd for $C_{17}H_{26}O_2$: C, 77.81; H, 9.99 Found: C, 77.89; H, 10.02.

3α-Acetoxy-2-norterrecyclan-2-one (32). A solution of allylic acetate **31** (R = Ac, 222 mg, 0.847 mmol) in 15 mL of CH_2Cl_2 was stirred and cooled at −78 °C as a stream of ozone was passed through the solution for 5 min. Dimethyl sulfide (2 mL) was then added at −78 °C, discharging the blue color. The solution was allowed to warm to room temperature, stirred for 2 h, and concentrated to afford a colorless oil. Flash chromatography (hexane/Et_2O 3:1) as eluant gave 159 mg (71%) of pure keto acetate **32** as a colorless oil. IR (neat): ν_{max} 1745 cm^{-1}. ^{1}H NMR: δ 0.92 (d, 3H, J = 7.1), 1.13 (s, 3H), 1.23 (dd, 1H, J = 8.1, 14.6), 1.26 (s, 3H), 1.50 (m, 1H), 1.58 (d, 1H, J = 14.4), 1.65 (ddd, 1H, J = 3.4, 5.9, 13.7), 1.71 (d, 1H, J = 14.4), 1.85−1.96 (m, 3H), 2.07 (s, 3H), 2.15 (app quintet, 1H, J = 6.8), 2.49 (dt, 1H, J = 9.0, 14.9), 2.61 (t, 1H, J = 9.7), 5.35 (dd, 1H, J = 4.4, 8.8). ^{13}C NMR: δ 17.11, 20.87, 26.19, 26.59, 27.98, 30.50, 34.28, 34.54, 40.16, 46.16, 50.06, 51.36, 61.43, 74.07, 170.13, 214.18. Anal. Calcd for $C_{16}H_{24}O_3$: C, 72.69; H, 9.15 Found: C, 72.89; H, 9.29.

2-Norterrecyclan-2-one (33). A solution of keto acetate **32** (123 mg, 0.466 mmol) in 5 mL of $EtNH_2$ was stirred and cooled at −78 °C as several small pieces of lithium (45 mg, 6.42 mmol) were added. The reaction mixture was stirred for 5 min at which time a blue color persisted. 3-Hexyne was added at −78 °C, which discharged the blue color, and the subsequent yellow color was discharged by adding methanol. The $EtNH_2$ was allowed to evaporate, and the resulting white residue was partitioned between Et_2O (10 mL) and water (10 mL). The Et_2O layer was dried ($MgSO_4$) and concentrated to give a mixture of ketone and alcohols from over-reduction. The mixture was dissolved in 3 mL of CH_2Cl_2 and *N*-methylmorpholine *N*-oxide (120 mg, 0.89 mmol), 150 mg of powdered 4 Å molecular sieves and (15 mg, 0.034 mmol) of tetra-*n*-propylammonium perruthenate were added. The suspension was stirred for 15 min before filtering through a small plug of silica gel. Flash chromatography with (hexane/Et_2O 6:1) as eluant gave 65 mg (69%) of pure ketone **33** as a colorless oil. IR (neat) ν_{max} 1744 cm^{-1}. ^{1}H NMR: δ 0.84 (d, 3H, J = 7.1), 1.12 (s, 3H), 1.18 (dd, 1H, J = 6.8, 14.6), 1.23 (s, 3H), 1.43−1.53 (m, 1H), 1.47 (d, 1H, J = 14.4), 1.60−1.65 (m, 1H), 1.67 (d, 1H, J = 14.4), 1.87 (t, 1H, J = 3.4), 1.90−2.09 (m, 4H), 2.14 (m, 1H), 2.32 (dd, 1H, J = 8.8, 7.3), 2.37−2.47 (m, 1H). ^{13}C NMR: δ 17.56, 23.98, 26.14, 26.93, 27.86, 34.89, 34.94, 39.15, 39.94, 48.12, 49.76, 50.41, 62.16, 222.60. Anal. Calcd for $C_{14}H_{22}O$: C, 81.49; H, 10.75. Found: C, 81.50; H, 10.72.

β-Terrecyclene (34). A solution of potassium *tert*-butoxide (62 mg, 0.56 mmol) in 1.2 mL of THF was stirred as methyltriphenylphosphonium bromide (234 mg, 0.656 mmol) was added.[31] The resulting bright yellow solution was refluxed for 20 min before ketone **32** (33 mg, 0.16 mmol) was added. The solution was heated at reflux, and the reaction progress was monitered by TLC. After 3 h the solution was cooled to room temperature and diluted with 10 mL of pentane. The pentane layer was washed with water (2 × 10 mL) and dried over $MgSO_4$. Flash chromatography with pentane as the eluant afforded 20 mg (60%) of β-terrecyclene (**34**). Elution with 6:1 hexanes/Et_2O as eluent afforded 7 mg (21%) of recovered ketone **33**. Data for **34**, ^{1}H NMR: δ 0.87 (d, 3H, J = 7.3), 1.07 (s, 3H), 1.16 (s, 3H), 1.18−1.25 (m, 1H), 1.39−1.50 (m, 1H), 1.51−1.61 (m, 4H), 1.64−1.86 (m, 3H), 1.90−2.06 (m, 3H), 2.08−2.19 (m, 1H), 2.47 (ddq, 1H, J = 15.9, 7.6, and 1.7), 4.54 (bs, 1H), 4.81 (bs, 1H). Anal. Calcd for $C_{15}H_{24}$: C, 88.16; H, 11.84 Found: C, 87.98; H, 11.90.

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Supporting Information Available: X-ray crystallographic data for **18**α-OH, **31**-OH, and **25** (123 pages). This material is contained in libraries on microfiche, immediately follows this article in the microfilm version of the journal, and can be ordered from the ACS; see any current masthead page for ordering information.

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