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Registry No. 1·2·13H_2O, 137122-82-8; 91·3·2H_2O, 137122-84-0; 3·4·3CH_3OH, 137143-71-6.

Supplementary Material Available: Tables of thermal parameters, bond lengths and bond angles, and calculated positional parameters and estimated standard deviations for the different complexes (22 pages). Ordering information is given on any current masthead page.

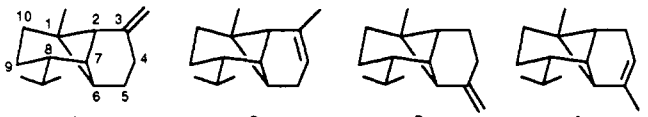
Total Syntheses of (±)-α- and (±)-β-Copaene and Formal Total Syntheses of (±)-Sativene, (±)-*cis*-Sativenediol, and (±)-Helminthosporal†

Ernest Wenkert,* Brett C. Bookser, and Thomas S. Arrhenius

Contribution from the Department of Chemistry (0506), University of California—San Diego, La Jolla, California 92093. *Received April 29, 1991*

Abstract: Conversion of the previously reported, carvacrol-based 4(*S**)-isopropyl-7(*R**)-chlorobicyclo[3.1.1]heptan-6-one and its bromo equivalent into (±)-α- and (±)-β-copaene is described. Model 5-nor-β-copaene was synthesized in the following manner: (a) γ-(trimethylsilyl)propargyllithium addition, (b) tri-*n*-butylstannane-induced, dehalogenative, free-radical cyclization and either fluoride-promoted or *p*-toluenesulfinic acid-catalyzed desilylation in the proper sequence, and (c) free-radical deoxygenation of the resultant tricyclic alcohol via a thioester. The β-copaene synthesis followed a similar procedure except for the addition of the lithio derivative of δ-(trimethylsilyl)homopropargyl *p*-tolyl sulfone in step a, sodium amalgam reduction of the intermediate sulfones either before or following step b, and alcohol deoxygenation by photolysis of an acetate in step c. Treatment of (±)-β-copaene with hydrogen iodide caused isomerization into (±)-α-copaene. Variation of the β-copaene synthesis scheme permitted a tie-up with sativene. Thus, ozonolysis of the 6-hydroxy-5-(*p*-tolylsulfonyl)-β-copaene intermediate followed by base-induced sulfinate elimination, acid- or base-catalyzed skeletal rearrangement, monothioketal formation, and desulfurization yielded a ketone, whose one-step transformation into (±)-sativene has been reported earlier. Finally, borohydride reduction of the sulfinate elimination product, acid-promoted skeletal rearrangement, and methyllithium addition led to an alcohol, whose conversion into (±)-*cis*-sativenediol and (±)-helminthosporal has been recorded earlier.

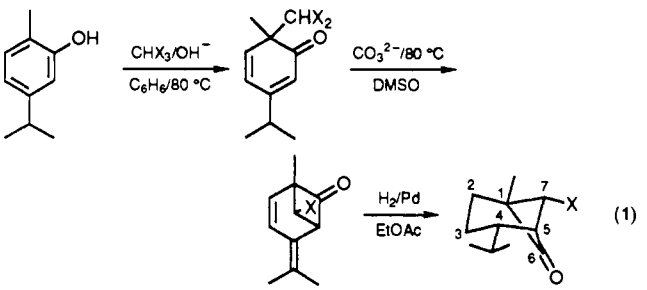
β-Copaene (**1**), α-copaene (**2**), β-ylangene (**3**), and α-ylangene (**4**) are tricyclic sesquiterpenes, whose unusual ring skeletons make them challenging goals of total synthesis. Early constructions



1 **2** **3** **4**

of two or more of these natural products depended on intramolecular displacements within *cis*-decalin frames[1,2] or on an intramolecular ene–ketene cyclization[3] for the formation of the central four-membered ring and also depended on the isopropyl group being attached to its cyclohexane nucleus at a late stage of the reaction sequences.[1-3] The absence of stereochemical control in the introduction of the three-carbon side chain in two of the three syntheses[2,3] and low control in one approach of the third synthesis[1] led to copaene–ylangene pairs as the final products. For this reason it was of interest to develop yet another route of synthesis, whose aim would be the formation of a unique sesquiterpene, e.g., β-copaene (**1**).

The new synthesis was predicated on early construction of the cyclobutane and isopropylated cyclohexane nuclei in configurationally correct forms, possessing properly placed functional groups for elaboration of the olefinic six-membered ring. This task has been accomplished some time ago in the four-step buildup of ketones **5** via Reimer–Tiemann chemistry on carvacrol (eq 1).[4,5] The remaining endeavor required the utilization of the halo and carbonyl groups of the ketones for the introduction of the third,



(1)

5a, X = Cl
b, X = Br

stereochemically inconsequential ring. It was hoped that a reaction sequence would be initiated by addition of an acetylene-bearing chain to the carbonyl function, fashioning a free-radical cyclization[6] in the direction of the β-copaene system by reductive

† Presented as an invited lecture at the 17th International Symposium on the Chemistry of Natural Products, New Delhi, India, February 4–9, 1990.

(1) Heathcock, C. H.; Badger, R. A.; Patterson, J. W., Jr. *J. Am. Chem. Soc.* **1967**, *89*, 4133.
(2) Corey, E. J.; Watt, D. S. *J. Am. Chem. Soc.* **1973**, *95*, 2303.
(3) Snider, B. B.; Kulkarni, Y. S.; Niwa, M.; Ron, E. *J. Org. Chem.* **1987**, *52*, 1568.
(4) Wenkert, E.; Bakuzis, P.; Baumgarten, R. J.; Doddrell, D.; Jeffs, P. W.; Leicht, C. L.; Mueller, R. A.; Yoshikoshi, A. *J. Am. Chem. Soc.* **1970**, *92*, 1617.
(5) Wenkert, E.; Arrhenius, T. S.; Bookser, B.; Guo, M.; Mancini, P. *J. Org. Chem.* **1990**, *55*, 1185.
(6) (a) Giese, B. *Radicals in Organic Synthesis; Formation of Carbon–Carbon Bonds*; Pergamon Press: Oxford, 1986. (b) Neumann, W. P. *Synthesis* **1987**, 655. (c) Ramaiah, M. *Tetrahedron* **1987**, *43*, 3541. (d) Curran, D. P. *Synthesis* **1988**, *417*, 489. (e) Thebtaranonth, C.; Thebtaranonth, Y. *Tetrahedron* **1990**, *46*, 1385.

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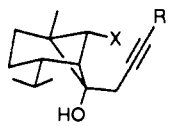
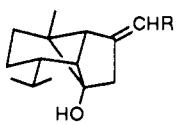
interaction of the halocarbon with the acetylenic linkage.

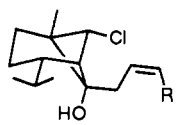
5-Nor-β-copaene. In order to test the efficacy of the reactions needed to convert ketones **5** into the copaene system, a model study was initiated, which was expected to lead to the lower homologue of β-copaene (**1**). Addition of [γ-(trimethylsilyl)propargyl]lithium[7] to ketones **5a** and **5b** yielded alcohols **6a** (84%) and **6b**[8] (99%), respectively, whose fluoride-induced desilylation afforded homopropargyl alcohols **6c** (89%) and **6d** (74%), respectively. The last two substances were ideally suited for reductive ring closure by free radical means[9] and, hence, were exposed to tri-*n*-butylstannane (Bu_3SnH) in the presence of the radical initiator, azobis(isobutyronitrile) (AIBN). Whereas the trishomopropargyl bromide **6d** was converted thereby into the cyclized product **7a**, the chloro equivalent **6c** underwent stannane–acetylene addition[10] instead. Destannylation of the resultant adduct (**8a**) with *p*-toluenesulfinic acid in wet acetonitrile produced homoallyl alcohol **8b** (in 40% two-step yield). In view of the low rate of chlorine atom abstraction from halide **6c**, hydrostannylation of its acetylenic side chain had overtaken the desired cyclization process. In order to reduce the hydrostannylation rate, the reductive cyclization was carried out on the sterically more encumbered silylacetylene **6a** and led to tricycle **7b**. Their desilylation with *p*-toluenesulfinic acid in wet acetonitrile[11] furnished 5-nor-β-copaen-6-ol (**7a**) (in 78% two-step yield). Thus, both chloro ketone **5a** and bromo ketone **5b** had been transformed efficiently into tricyclic alcohol **7a** (65% yield) in three steps.



6a, R = $SiMe_3$, X = Cl
b, R = $SiMe_3$, X = Br
c, R = H, X = Cl
d, R = H, X = Br

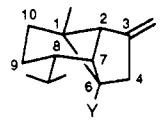


7a, R = H
b, R = $SiMe_3$

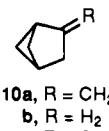


8a, R = Sn(*n*-Bu)$_3$
b, R = H

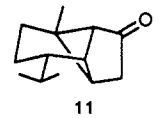
Finally, alcohol **7a** had to be deoxygenated, and a free-radical reduction[12] was chosen for this purpose. Treatment of the alcohol with *tert*-butyllithium and thereafter with phenyl chlorothionocarbonate[13] afforded thiocarbonate **9a** (92%), whose Bu_3SnH–AIBN reduction[13] in boiling cumene led to 5-nor-β-copaene (**9b**) (25%), thiol **9c** (14%), ether **9d** (15%), and acetal **9e** (trace).[14] Thus the goal of the model study had been reached, although the last step had been low-yielding.[15]



9a, Y = $OCOC_6H_5$
b, Y = H
c, Y = OCH_2SH
d, Y = $OCH_2OC_6H_5$



10a, R = CH_2
b, R = H_2
c, R = O



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The norcopaene **9b** exhibited several spectral properties characteristic of its structure. The infrared absorption bands (3070, 1670, and 860 cm^{-1}) associated with the exocyclic methylene group and the ^1H chemical shifts (4.69 and 4.92 ppm singlets) of the olefinic hydrogens were reminiscent of those of structurally related 2-methylenebicyclo[2.1.1]hexane (**10a**) (IR 3084, 1670, and 870 cm^{-1}; ^1H NMR δ 4.65 and 4.95).[16] The four-bond, H(2)–H(6), *W* coupling of 7 Hz was identical with that of the bridgehead hydrogens of bicyclo[2.1.1]hexane (**10b**).[17] Furthermore, the carbonyl infrared absorption band (1755 cm^{-1}) and the bridgehead hydrogen *W* coupling (^4J = 7 Hz) of tricyclic ketone **11**, a product of the ozonolysis of 5-nor-β-copaene (**9b**), were identical with the like physical properties of model bicyclo[2.1.1]hexan-2-one (**10c**).[18]

In an attempt to transform a nor-β-copaene system into a nor-α-copaene moiety, nor-β-copaene derivative **7a** was submitted to treatment with strong base ($K^+{}^-HN(CH_2)_3NH_2$ in $H_2N(CH_2)_3NH_2$).[19] However, instead of double bond migration, ring

(7) Corey, E. J.; Kirst, H. A. *Tetrahedron Lett.* **1968**, 5041.

(8) The stereochemistry at the oxycarbon site, while unique, remained obscure until the subsequent cyclizations confirmed the alcohol structures. It is noteworthy that the addition of a smaller organometallic reagent, i.e., methyllithium, to ketone **5b** yielded a mixture of stereoisomeric alcohols.

(9) See refs 6a–e. For recent work, see: (a) Harling, J. D.; Motherwell, W. B. *J. Chem. Soc., Chem. Commun.* **1988**, 1380. (b) Clive, D. L. J.; Mohammed, A. H. *Heterocycles* **1989**, *28*, 1157. (c) Ichinose, Y.; Matsunaga, S.; Fugami, K.; Oshima, K.; Utimoto, K. *Tetrahedron Lett.* **1989**, *30*, 3155. (d) Oumar-Mahamat, H.; Moustrou, C.; Surzur, J.-M.; Bertrand, M. P. *J. Org. Chem.* **1989**, *54*, 5684. (e) Curran, D. P.; Chen, M.-H.; Kim, D. J. *J. Am. Chem. Soc.* **1989**, *111*, 6265. (f) Molander, G. A.; Kenny, C. *Ibid.* **1989**, *111*, 8236. (g) Curran, D. P.; Chen, M.-H.; Spletzer, E.; Seong, C. M.; Chang, C.-T. *Ibid.* **1989**, *111*, 8872. (h) Wu, G.; Cederbaum, F. E.; Negishi, E. *Tetrahedron Lett.* **1990**, *31*, 493. (i) Clive, D. L. J.; Manning, H. W.; Boivin, T. L. B. *J. Chem. Soc., Chem. Commun.* **1990**, 972. (j) Cossy, J.; Belotti, D.; Pete, J. P. *Tetrahedron* **1990**, *46*, 1859. (k) Kilburn, J. D. *Tetrahedron Lett.* **1990**, *31*, 2193. (l) Sha, C.-K.; Jean, F. S.; Wang, D.-C. *Ibid.* **1990**, *31*, 3745. (m) Knapp, S.; Gibson, F. S.; Choe, Y. H. *Ibid.* **1990**, *31*, 5397. (n) Boger, D. L.; Ishizaki, T.; Kitos, P. A.; Suntornwat, O. *J. Org. Chem.* **1990**, *55*, 5823. (o) Molander, G. A.; Harring, L. S. *Ibid.* **1990**, *55*, 6171. (p) Curran, D. P.; Shen, W.; Zhang, J.; Heffner, T. A. *J. Am. Chem. Soc.* **1990**, *112*, 6738. (q) Schwartz, C. E.; Curran, D. P. *Ibid.* **1990**, *112*, 9272. (r) Curran, D. P.; Seong, C. M. *Ibid.* **1990**, *112*, 9401. (s) Sharma, G. V. M.; Vepachedu, S. R. *Tetrahedron* **1991**, *47*, 519. (t) Ryu, I.; Kusano, K.; Hasegawa, M.; Kambe, N.; Sonoda, N. *J. Chem. Soc., Chem. Commun.* **1991**, 1018. (u) Clive, D. L. J.; Khodabocus, A.; Vernon, P. G.; Angoh, A. G.; Bordeleau, L.; Middleton, D. S.; Lowe, C.; Kellner, D. *J. Chem. Soc., Perkin Trans. 1* **1991**, 1433. (v) Lolkema, L. D. M.; Hiemstra, H.; Ghouch, A. A. A.; Speckamp, W. N. *Tetrahedron Lett.* **1991**, *32*, 1491. (w) Inanga, J.; Ujikawa, O.; Yamaguchi, M. *Ibid.* **1991**, *32*, 1737. (x) Tanaka, T.; Bannai, K.; Hazato, A.; Koga, M.; Kurozumi, S.; Kato, Y. *Tetrahedron* **1991**, *47*, 1861. (y) Rochigneux, I.; Fontanel, M.-L.; Malanda, J.-C.; Doutheau, A. *Tetrahedron Lett.* **1991**, *32*, 2017. (z) Iwasa, S.; Yamamoto, M.; Kohmoto, S.; Yamada, K. *J. Org. Chem.* **1991**, *56*, 2849. (a') Clive, D. L. J.; Daigneault, S. *Ibid.* **1991**, *56*, 3801. (b') Curran, D. P.; Abraham, A. C.; Hongtao, L. *Ibid.* **1991**, *56*, 4335. (c') Feldman, K. S.; Burns, C. J. *Ibid.* **1991**, *56*, 4601. (d') Inokuchi, T.; Kawafuchi, H.; Torii, S. *Ibid.* **1991**, *56*, 4983. (e') Rao, S. A.; Knochel, P. *J. Am. Chem. Soc.* **1991**, *113*, 5735.

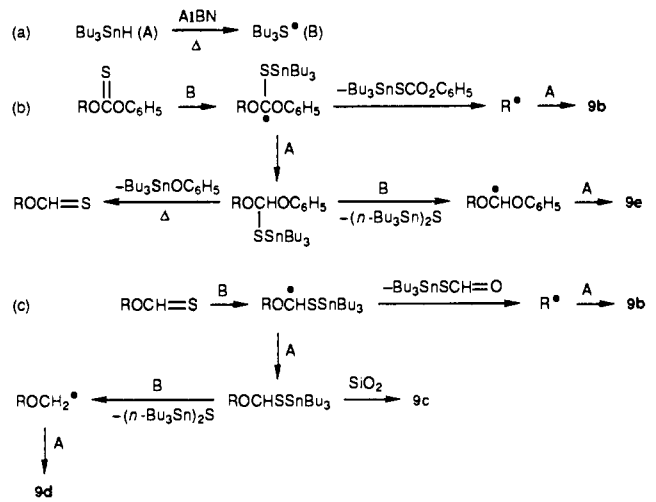
(10) (a) Chen, S.-M. L.; Schaub, R. E.; Grudzinskas, C. V. *J. Org. Chem.* **1978**, *43*, 3450. (b) Taddei, M.; Nativi, C. *Ibid.* **1988**, *53*, 820.

(11) Büchi, G.; Wuest, H. *Tetrahedron Lett.* **1977**, 4305.

(12) (a) Hartwig, W. *Tetrahedron* **1983**, *39*, 2609. (b) Portella, C.; Deshayes, H.; Pete, J. P. *Ibid.* **1984**, *19*, 3635. (c) Prisbe, L. J.; Martin, J. C. *Synth. Commun.* **1985**, *15*, 401. (d) Dolan, S. C.; MacMillan, J. *J. Chem. Soc., Chem. Commun.* **1985**, 1588. (e) Barton, D. H. R.; Crich, D. *J. Chem. Soc., Perkin Trans. 1* **1986**, 1603. (f) Barton, D. H. R.; Jaszberenyi, J. Cs. *Tetrahedron Lett.* **1989**, *30*, 2619.

(13) Robins, M. J.; Wilson, J. S.; Hansske, F. *J. Am. Chem. Soc.* **1983**, *105*, 4059.

(14) The complex product mixture was most probably formed by the following pathway (Barton, D. H. R.; Crich, D.; Löbberding, A.; Zard, S. Z. *Tetrahedron* **1986**, *42*, 2329):



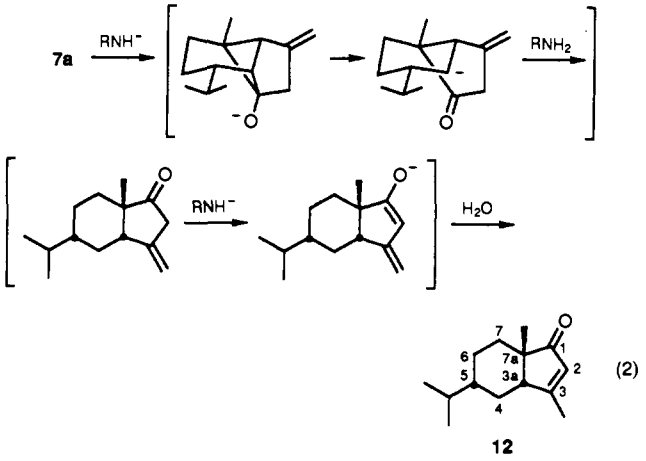
(15) The low-level reactivity of thioester **9a** with respect to deoxygenation is reminiscent of the complete suppression of free-radical deoxygenation of a norbornan-1-ol derivative via a thioester intermediate (McMurry, J. E.; Haley, G. J.; Matz, J. R.; Clardy, J. C.; Van Duyne, G.; Gleiter, R.; Schäfer, W.; White, D. H. *J. Am. Chem. Soc.* **1986**, *108*, 2932).

(16) de Mayo, P.; Charlton, J. L.; Skattebol, L. *Tetrahedron Lett.* **1965**, 4679.

(17) Pretsch, E.; Clerc, T.; Seibl, J.; Simon, W. *Tables of Spectral Data for Structure Determination of Organic Compounds*; Springer Verlag: Berlin, 1983.

(18) Bond, F. T.; Jones, H. L.; Scerbo, L. *Tetrahedron Lett.* **1965**, 4685.

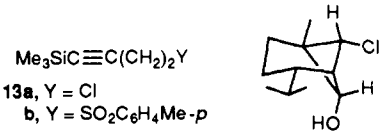
fragmentation took place (cf. eq 2), yielding bicyclic enone **12**.



(2)

12

β-Copaene. In order to build up the actual sesquiterpene by the reaction route utilized for the nor series, it was necessary to prepare four-carbon, acetylenic side chain equivalents of alcohols **6a** and **6b** and hope that the free-radical cyclization of these intermediates would proceed as well as in the nor series, despite the less favorable transition state in six-membered ring-forming processes.[20] The first attempt of construction of an alcohol **6a** equivalent failed, when a reaction between ketone **5a** and the Grignard reagent from chloride **13a**[21] led to the reduction product **14** (69%) (1-(trimethylsilyl)-3-buten-1-yne presumably being the other product) instead of the expected adduct. Hence, the chloride was converted into sulfone **13b** (62%) by displacement with sodium *p*-toluenesulfinate and the lithio derivative (**15**) of the sulfone, prepared by treatment of sulfone **13b** with *n*-butyllithium, which was used for all subsequent ketone addition reactions.



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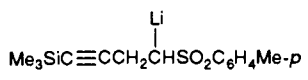

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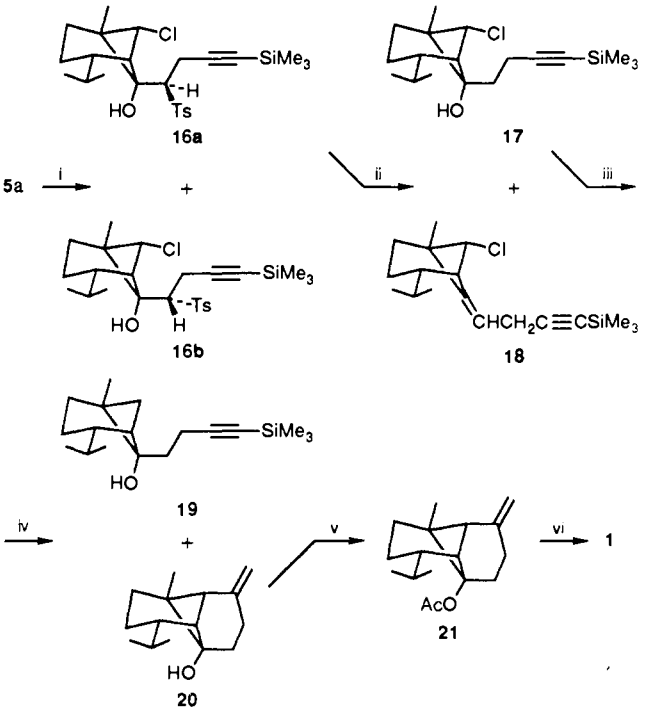
As Scheme I illustrates, exposure of the lithiated sulfone (**15**) to ketone **5a** yielded a mixture of diastereomeric sulfones, **16a** (72%) and **16b** (17%), the sodium amalgam reduction[22] of which afforded alcohol **17** (49%) as well as enynes **18** (35%). Treatment

Scheme I[a]



[a] (i) **15**, THF, −78 °C. (ii) Na(Hg), HPO_4^{2-}, MeOH, THF, −20 °C. (iii) 0.10 M in C_6H_6, Bu_3SnH, AIBN, Δ. (iv) TsH, MeCN (2% H_2O), Δ. (v) Ac_2O, Et_3N, γ-(dimethylamino)pyridine (DMAP), Et_2O. (vi) *hν* (254 nm), HMPA (5% H_2O).

of chloro alcohol **17** with the Bu_3SnH–AIBN reagent[20] and subsequently with *p*-toluenesulfinic acid in wet acetonitrile gave reduction product **19** (57%) and reductive cyclization product **20** (32%). Acylation of the latter and photolysis of the resultant acetate (**21**) (85%) in wet hexamethylphosphoramide (HMPA)[12b] furnished (±)-β-copaene (**1**) (29%).

Assignment of the stereochemistry of sulfones **16a** and **16b** was based on the assumption of the **5a**–**15** addition process being governed by Cram's rule of asymmetric induction.[23] Both adducts exhibited appreciable hydrogen bonding between their hydroxy and sulfone groups, as indicated by the absence of any effect on the intensity of the infrared absorption bands (3510 and 3500 cm^{-1}, respectively) of the hydroxy groups on sample dilution and by the low rate of deuterium exchange of the two alcohols in comparison with the rate of hydrogen–deuterium exchange in alcohol **17**. It was fortunate that the sulfone reduction had yielded the desulfonylated alcohol **17**, in view of the known tendency toward olefin formation on chemical reduction of β-hydroxy sulfones.[24] Hence the appearance of side products **18** came as no surprise. However, had enynes **18** been the sole or major products, the desulfonylation would have had to be postponed until after cyclization (vide infra).

Tin hydride reduction of chloride **17** had furnished the sought-after 6-hydroxy-β-copaene (**20**)—an experience which can be added to the small list of methylenecyclohexane-forming reactions of terminal acetylenic carbon radicals[20]—although dechloroacetylene **19** had been the major product. It is conceivable that the noncyclizative dechlorination competes favorably with the cyclization as a consequence of the interference of an irreversible 1,5-hydrogen shift of the initial carbon radical intermediate (eq 3).[25]

Whereas, in principle, deoxygenation of hydroxycopaene **20** should have been able to follow the reaction pattern of the nor

(19) (a) Brown, C. A. *Synthesis* **1978**, 754. (b) Brown, C. A.; Jadhav, P. K. *Org. Synth.* **1987**, *65*, 224.

(20) Reactions promoted by $R_3Sn^{\cdot}$ species: (a) Crandall, J. K.; Keyton, D. J. *Tetrahedron Lett.* **1969**, 1653. (b) Büchi, G.; Wuest, H. *J. Org. Chem.* **1979**, *44*, 546. (c) Bachi, M. D.; Frolow, F.; Hoornaert, C. *Ibid.* **1983**, *48*, 1841. (d) Clive, D. L. J.; Beaulieu, P. L.; Set, Lu *Ibid.* **1984**, *49*, 1313. (e) Kametani, T.; Chu, S.-D.; Itoh, A.; Maeda, S.; Honda, T. *Ibid.* **1988**, *53*, 2683. (f) Girijavallabhan, V. M.; Ganguly, A. K. *Heterocycles* **1989**, *28*, 47. (g) De Mesmaeker, A.; Hoffmann, P.; Ernst, B. *Tetrahedron Lett.* **1989**, *30*, 57. (h) Morikawa, T.; Nishikawa, T.; Kobayashi, Y. *Ibid.* **1989**, *30*, 2407. (i) Rao, A. V. R.; Yadav, J. S.; Rao, S.; Chandrasekhar, S. *J. Chem. Soc., Perkin Trans. 1* **1990**, 1211. (j) Boger, D. L.; Mathvink, R. J. *J. Am. Chem. Soc.* **1990**, *112*, 4003. (k) Boger, D. S.; Coleman, R. S. *J. Org. Chem.* **1990**, *55*, 5442. Reactions induced by other reagents: (l) Crandall, J. K.; Battion, P.; Wehlacz, J. T.; Bindre, R. *J. Am. Chem. Soc.* **1975**, *97*, 7171. (m) Pradhan, S. K.; Radhakrishnan, T. V.; Subramanian, R. *J. Org. Chem.* **1976**, *41*, 1943. (n) Pradhan, S. K.; Kadam, S. R.; Kolhe, J. N.; Radhakrishnan, T. V.; Sohani, S. V.; Thaker, V. B. *Ibid.* **1981**, *46*, 2622. (o) Crandall, J. K.; Michaely, W. J. *Ibid.* **1984**, *49*, 4244. (p) Pattenden, G.; Robertson, G. M. *Tetrahedron* **1985**, *41*, 4001. (q) Cossy, J.; Belotti, D.; Pete, J. P. *Tetrahedron Lett.* **1987**, *28*, 4545. (r) Bailey, W. F.; Ovaska, T. V. *Ibid.* **1990**, *31*, 627. (s) Bhandal, H.; Patel, V. F.; Pattenden, G.; Russell, J. J. *J. Chem. Soc., Perkin Trans. 1* **1990**, 2691. (t) Shim, S. C.; Hwang, J.-T.; Kang, H.-Y.; Chang, M. H. *Tetrahedron Lett.* **1990**, *31*, 4765. (u) Monteiro, N.; Balme, G.; Gore, J. *Tetrahedron Lett.* **1991**, *32*, 1645.

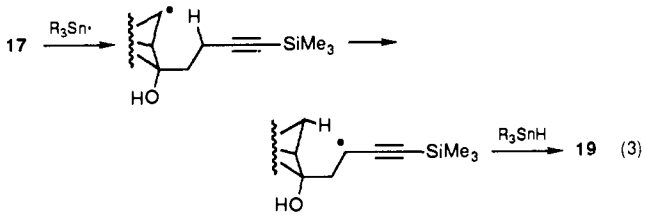
(21) Conia, J. M.; Drouin, J.; Leyendecker, F. *Tetrahedron* **1980**, *36*, 1203.

(22) Trost, B. M.; Arndt, H. C.; Strege, P. E.; Verhoegen, T. R. *Tetrahedron Lett.* **1976**, 3477.

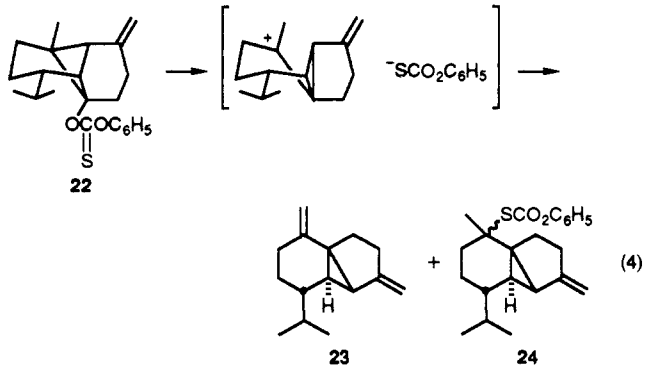
(23) (a) Cram, D. J.; Abd Elhafez, F. A. *J. Am. Chem. Soc.* **1952**, *74*, 5828. (b) Zimmerman, H. E.; Traxler, M. J. *Ibid.* **1957**, *79*, 1920.

(24) Julia, M.; Paris, J.-M. *Tetrahedron Lett.* **1973**, 4833.

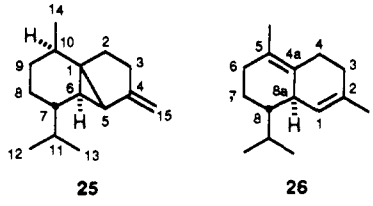
(25) For a similar reaction involving a carbon radical yielding an allyl radical on 1,5-hydrogen rearrangement, see: (a) Beckwith, A. L. J.; Moad, G. *J. Chem. Soc., Chem. Commun.* **1974**, 472. (b) Leonard, W. R.; Livinghouse, T. *Tetrahedron Lett.* **1985**, *26*, 6431.



series (vide supra), the two-step reaction sequence of thioester formation and reduction failed as a result of the facile decomposition of the intermediate thioesters and thus impelled the use of the reductive photolysis of acetate **21**. In an attempt to prepare thioester **22** by treatment of alcohol **20** first with potassium hydride in tetrahydrofuran (THF) and then with phenyl chlorothionocarbonate in HMPA,[26] the copaene system underwent molecular rearrangement into the cubebene system[27] in the form of diene **23** (26%) and thioester **24** (22%) (eq 4). The structures of these

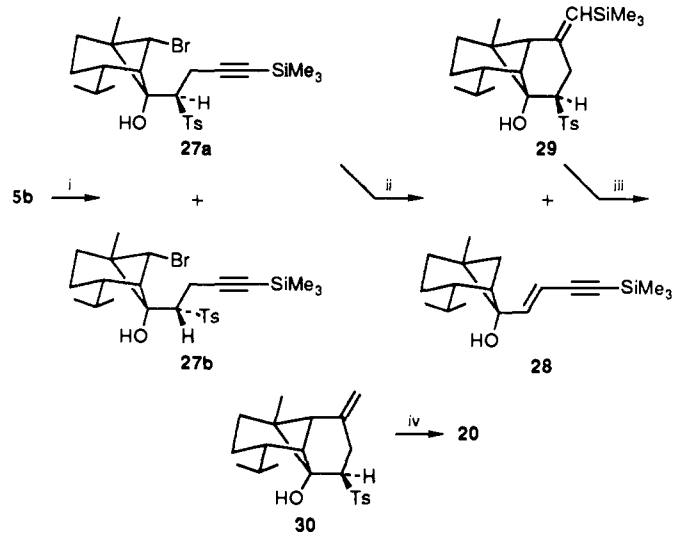


products were determined by their infrared and ^1H and ^{13}C NMR spectral characteristics, as well as spectral comparison with derivatives of β-cubebene (**25**).[28] The presence of a carbonyl (in contrast to thiocarbonyl) group in ester **24** was verified by the compound's infrared carbonyl band (1725 cm^{-1}) and carbonyl ^{13}C chemical shift (168.8 ppm). Raney nickel desulfurization of thioester **24**, in an attempt to synthesize β-cubebene (**25**), led to one more molecular rearrangement and afforded racemic δ-cadinene (**26**) (68%), spectrally identical with the natural product.[29,30] This constitutes the first total synthesis of the sesquiterpene.[31]



An alternate synthesis of β-copaene could be envisaged to follow a reaction route in which the desulfonylation–cyclization sequence of Scheme I would be inverted. This variation was of special significance in light of the fact that bromo sulfones **27a** and **27b**,

Scheme II[a]



[a] (i) **15**, THF, −78 °C. (ii) 0.10 M in C_6H_6, Bu_3SnH, AIBN, Δ. (iii) TsH, MeCN (2% H_2O), Δ. (iv) Na(Hg), HPO_4^{2-}, MeOH, THF, −20 °C.

prepared (in 72 and 10% yields, respectively) by addition of the lithiated sulfone (**15**) to ketone **5b** (Scheme II), could not be desulfonylated without appreciable bromide reduction. Scheme II portrays the alternate reaction pathway (limited to the bromo compound series for ease of understanding). Exposure of sulfone **27a** to the R_3SnH–AIBN reagent yielded a mixture of hydroxy enyne **28** (47%) and tricyclic sulfone **29** (42%), while the same reaction with chloro sulfone **16a** led to the same mixture of products (in 24 and 37% yields, respectively). Desilylation of tricycle **29** gave sulfone **30** (79%), whose sodium amalgam reduction formed 6-hydroxy-β-copaene (**20**) (67%). Deoxygenation of the latter has been described above (Scheme I).

When in the formation of hydroxy sulfones **27a** and **27b** (or, earlier, hydroxy sulfones **16a** and **16b**) an excess of *n*-butyllithium had been used for the preparation of the organolithium reagent **15**, the sulfones underwent *p*-toluenesulfinate elimination leading to enynes **31**.[32,33] The conjugated olefinic acetylenes possessed a trans double bond, as illustrated by the 17 Hz coupling of the olefinic hydrogens in their ^1H NMR spectra. The formation of enyne **28** in the tin hydride reduction of sulfones **16a** and **27a** is in accord with the intermediacy of a 1,5-hydrogen shift (eq 3) and final arylsulfinyl radical extrusion.[33] The cyclization–desilylation sequence of Scheme II could be inverted. Thus, treatment of sulfone **27a** with tetrabutylammonium fluoride gave sulfone **32**, whose tin hydride reduction afforded sulfone **30** (17% two-step yield).[34,35] The stereochemistry of the sulfone side chain in tricycle **30** was reflected by deshielding of H-7 (2.74 ppm) by the sulfonyl group (compared with $\delta_{H\text{-}7}$ = 2.38 ppm for tricycle **20**) and by the 20% H-5 signal enhancement on irradiation of the angular methyl singlet in an NOE experiment. Verification of the sulfone

(26) The rearrangement took place even in THF but was more efficient in HMPA.

(27) Cf. (a) Della, E. W.; Pigou, P. E.; Tsanaktsidis, J. *J. Chem. Soc., Chem. Commun.* **1987**, 833. (b) Schiesser, C. H.; Della, E. W.; Gill, P. M. W. *J. Org. Chem.* **1988**, *53*, 4354.

(28) (a) Ohta, Y.; Sakai, T.; Hirose, Y. *Tetrahedron Lett.* **1966**, 6365. (b) Kurosawa, E.; Kowata, N.; Suzuki, M. *Bull. Chem. Soc. Jpn.* **1981**, *54*, 2366. (c) Bohlmann, F.; Jakupovic, J.; Ahmed, M.; Wallmeyer, M.; Robinson, H.; King, R. M. *Phytochemistry* **1981**, *20*, 2383. (d) Bohlmann, F.; Jakupovic, J.; Vogel, W. *Ibid.* **1982**, *21*, 1153.

(29) (a) Dolinsky, M.; Wenninger, J. A.; Yates, R. L. *J. Assoc. Off. Anal. Chem.* **1967**, *50*, 1313. (b) Dev, S.; Nagasampagi, B. A.; Yankov, L. *Tetrahedron Lett.* **1968**, 1913.

(30) The authors express their thanks to Dr. A. Thomas (Firmenich S. A.) for a ^1H NMR spectrum of the compound.

(31) For the formation of δ-cadinene (**26**) from α-copaene (**2**) and α-cubebene on acid treatment, see: Ohta, Y.; Ohara, K.; Hirose, Y. *Tetrahedron Lett.* **1968**, 4181.

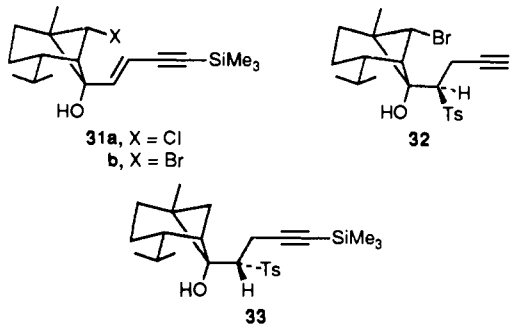
(32) For a similar reaction involving the formation of conjugated dienes by *tert*-butyllithium-induced sulfinate elimination from homoallyl aryl sulfones, see: Radisson, X.; Kwaitkowsky, P. L.; Fuchs, P. L. *Synth. Commun.* **1987**, *17*, 39.

(33) In view of the importance of a terminal, conjugated enyne system in natural products synthesis, this facile construction of the unusual chromophore is noteworthy. For previous enyne syntheses, see: (a) Miller, J. A.; Zweifel, G. *J. Am. Chem. Soc.* **1983**, *105*, 1383 and references therein. (b) Stille, J. K.; Simpson, J. H. *Ibid.* **1987**, *109*, 2138. (c) Stang, P. J.; Kitamura, T. *Ibid.* **1987**, *109*, 7561. (d) Overman, L. E.; Thompson, A. S. *Ibid.* **1988**, *110*, 2248. (e) Trost, B. M.; Kottirsch, G. *Ibid.* **1990**, *112*, 2816.

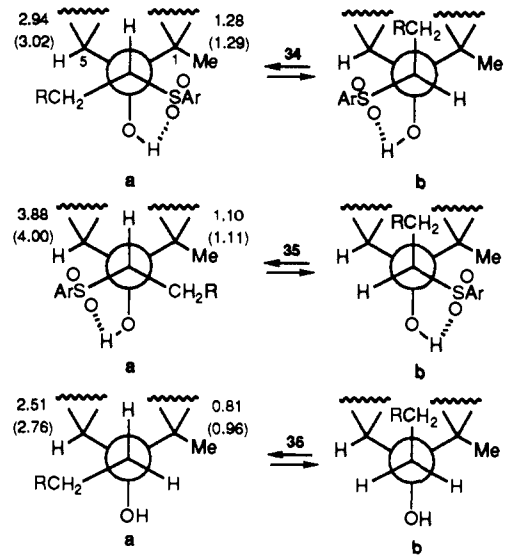
(34) The crude reaction mixture revealed the cyclized product to be admixed with desilyl-**28** (^1H NMR δ 5.76 (dd, 1, *J* = 17, 2 Hz, olefinic H), 6.60 (d, 1, *J* = 17 Hz, olefinic H)), which unfortunately could not be separated easily from the organotin side products.

(35) Comparison of the cyclization efficiency of the **32** → **30** reaction with the **27a** → **29** transformation shows the presence of a trimethylsilyl group on the carbon–carbon triple bond to enhance strongly the free-radical cyclization tendency (cf. ref 20a).

stereochemistry within a tricyclic framework now confirmed the stereochemical assignment of the sulfonyl function on the side chain of bicycles **16a**, **16b**, **27a**, and **27b**. Finally, it is worth noting that none of the reductive cyclizations (**16a** → **29**, **17** → **20**, **27a** → **29**, **32** → **30**) was dependent on substrate concentration.

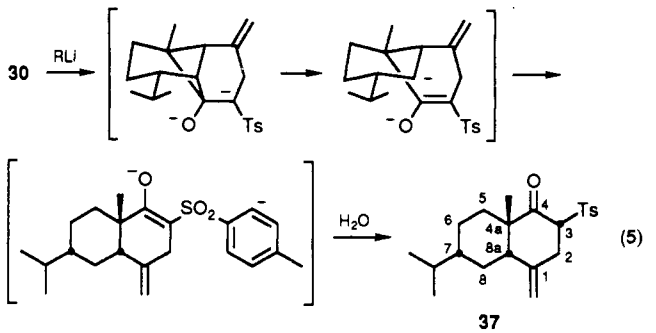


The minor products (**16b** and **27b**) of additions of lithiated homopropargyl sulfone (**15**) to ketones **5** proved to be useless for the β-copaene synthesis, since they resisted free-radical cyclization. Thus, for example, exposure of sulfone **27b** to the R_3SnH–AIBN reagent resulted in reductive debromination (**33**, 77%) and reductive debromination–desulfonylation (**28**, 15%). The striking difference in the cyclization behavior of the diastereomers **27a** and **27b** (as well as **16a** and **16b**) can be interpreted in terms of the dissimilarity of their conformations. Newman projections of the bond structure of the neighboring sulfonylated and hydroxylated carbons for **16a** (**27a**), **16b** (**27b**), and **17** (bromo equivalent of **17**) are shown in formulas **34**, **35**, and **36**, respectively, in the form of the most likely ground-state rotamers (a) and cyclization-mode rotamers (b). The ^1H NMR shifts of H-5

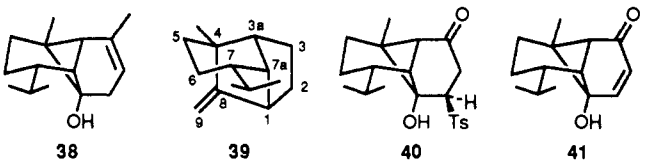


and the angular methyl group are good conformation indicators, since they reflect the proximity of the deshielding sulfonyl group. They are listed on the formulas (those of the bromo series are in parentheses) and substantiate the choice of ground-state rotamers on the basis of conformational analysis assumptions. Since the **35a** → **35b** rotamer change for the acquisition of a cyclization mode of the minor sulfone **16b** (**27b**) represents a much higher energy barrier than the **34a** → **34b** variation for the major sulfone **16a** (**27a**), the minor sulfone does not undergo cyclization. However, enough of a **35b** rotamer population must be present to permit a 1,5-hydrogen shift, leading to product **28**, to take place.

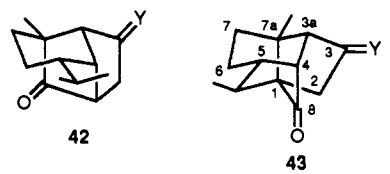
In an attempt to isomerize sulfone **30** to aid in its structure determination, the compound was treated with *n*-butyllithium (2 equiv) in hot THF. But instead of obtaining the C-5 epimer, the sulfone had undergone a drastic structural change reminiscent of the **7a** → **12** transformation, leading to bicyclic ketone **37** (eq 5). This conversion thus led to a substance with a *cis*-eudesmane configuration.



α-Copaene. Treatments of 6-hydroxy-β-copaene (**20**) as well as β-copaene (**1**) with hydrogen iodide in benzene solution[36] afforded 6-hydroxy-α-copaene (**38**) (94%) and (±)-α-copaene (**2**) (47%),[37] respectively. This completed the total syntheses of the racemic copaenic sesquiterpenes **1** and **2**.



Sativene. The availability of 6-hydroxy-5-(*p*-tolylsulfonyl)-β-copaene (**30**) from the above β-copaene synthesis (Scheme II) opened a road to the sativene (**39**) skeleton. It merely required some functional group manipulations and thereafter a skeletal rearrangement to accomplish the task. Ozonolysis of the olefin **30** and reductive workup of the ozonide furnished ketone **40** (83%), whose treatment with lithium diisopropylamide yielded the conjugated ketone **41** (92%). Being a vinylogous α-ketol, the latter was expected to undergo a semi-benzilic acid rearrangement, which was prone to expand the cyclobutanol and contract the cyclohexenone moieties, albeit in a stereochemical manner that was difficult to predict. Experience, however, showed the skeletal alteration to be biased toward the sativene structure. Thus, in methanolic hydrogen chloride or methanolic sodium methoxide solution, ketol **41** was transformed in 88% yield into ca. 3:1 and 14:1 mixtures, respectively, of diketones **42a** and **43a**.[38] Treatment of each diketone with ethane-1,2-dithiol and boron trifluoride produced monothioketals **42b** (90%) and **43b** (71%), respectively, whose reduction with Raney nickel afforded norsativone (**42c**) (65%) and 5-epinorsinularone (**43c**) (74%), respectively. In view of a previous transformation of the keto group of norsativone (**42c**) into an exocyclic methylene unit,[39] the present construction of ketone **42c** constitutes a formal total synthesis of (±)-sativene.[40]



a, Y = O
b, Y = $S(CH_2)_2S$
c, Y = H_2

(36) Cf. Snider, B. B.; Beal, R. B. *J. Org. Chem.* **1988** *53*, 4508.

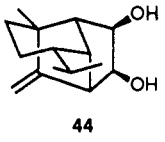
(37) Normally the copaene ring structure fragments into the cadinene system on exposure to mineral acids: (a) Dev, S.; Kapadia, V. H.; Nagasampagi, B. A.; Naik, V. G. *Tetrahedron* **1965**, *21*, 607. (b) Büchi, G.; Feairheller, S. H.; de Mayo, P.; Williams, R. E. *Ibid.* **1965**, *21*, 619. (c) Westfelt, L. *Acta Chem. Scand.* **1967**, *21*, 152. (d) Ohta, Y.; Ohara, K.; Hirose, Y. *Tetrahedron Lett.* **1968**, 4181.

(38) Rearrangements in dichloromethane solutions of hydrogen chloride or sodium hydride yielded 3:1 and 8:1 **42a**–**43a** mixtures, respectively.

(39) McMurry, J. E. *J. Am. Chem. Soc.* **1968**, *90*, 6821.

(40) In view of a former conversion of the carbonyl function of 5-epinorsinularone (**43c**) into an exocyclic methylene group (Wege, D.; Collins, P. A. *Aust. J. Chem.* **1979**, *32*, 1819), the present preparation of ketone **43c** represents also a formal total synthesis of the C(5) epimer of (±)-sinularene.

***cis*-Sativenediol and Helminthosporal.** The availability of intermediate ketol **41** placed two more sesquiterpenes, *cis*-sativenediol (**44**) and helminthosporal (**45**), within easy reach. For the attainment of this goal, a 2,3-dehydrosativene system was needed. Hence, the following experiments were undertaken.



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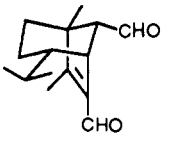

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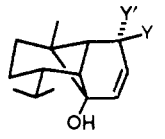
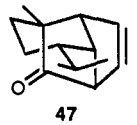
Sodium borohydride reduction of ketone **41** in the presence of cerium trichloride led to a ca. 7:1 mixture (84%) of diols **46a** and **46b**. Treatment of each isomer (or the mixture) with methanolic hydrogen chloride gave a ca. 3:1 mixture (76%) of olefinic ketones **47**[41,42] and **48**, whose resistance to chromatographic separation required postponement thereof until after the next reaction, i.e., methyllithium addition.[42] The latter process furnished a ca. 3:1 mixture (82%) of alcohols **49** and **50**. Since carbinol **49** has been transformed some time ago[42] into (±)-*cis*-sativenediol (**44**) and (±)-helminthosporal (**45**), the **41** → **49** reaction sequence completes a formal total synthesis of these racemic sesquiterpenes.



46a, Y = H, Y' = OH
b, Y = OH, Y' = H



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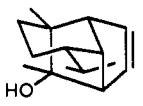
48



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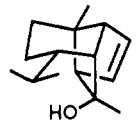

50

As the above discussion has illustrated, the copaene system is rich in chemistry and gives access to sesquiterpenes of a broad range of structure types. When added to the fact of ketone intermediates **5** now being available in optically pure form,[5] the above method of sesquiterpene construction has taken on the form of an all-powerful scheme of synthesis.

Experimental Section

Melting points were recorded on a Reichert micro hotstage and are uncorrected. Infrared spectra of CCl_4 solutions were observed on a Perkin-Elmer 1330 spectrophotometer. ^1H NMR spectra of $CDCl_3$ solutions were obtained on a General Electric QE-300 spectrometer, and ^{13}C NMR spectra of $CDCl_3$ solutions were performed on the same instrument, operating at 75.5 MHz in the Fourier transform mode. Carbon shifts are in parts per million downfield from Me_4Si ($\delta(Me_4Si) = \delta(CDCl_3) + 76.9$ ppm). Complete NMR signal assignments on selected samples are based on COSY and ^{13}C–^1H correlation experiments.

Solvents and reagents were purified according to established procedures.[43] The use of dry solvents indicates that the reactions were executed under nitrogen. The usual reaction workup entailed extracting the aqueous mixture with ether, washing the extract with water and brine, drying ($MgSO_4$), and evaporating under vacuum. Chromatography was performed on 60–200 mesh E. M. Davison type H silica gel (silica A), 70–230 mesh Merck Kieselgel 60 (silica B), and 150 mesh neutral alumina (activity III). Pasteur pipette flash chromatography involved the forcing of 0.5–1 mL of elution solvent per collected fraction through a 5.75-in. Pasteur pipette filled with adsorbent by the use of a 1-mL pipette bulb. Medium-pressure liquid chromatography (MPLC) took place on a Merck Lobar silica gel column with a Fluid Metering, Inc. pump.

1-Methyl-4(*S)-isopropyl-6(*R**)-(2-propynyl)-7(*R**)-chlorobicyclo[3.1.1]heptan-6-ol (6c) and Its Bromo Equivalent (6d).** A 2.5 M hexane solution of *n*-butyllithium (12.8 mL, 32 mmol) was added dropwise to a stirring solution of 3.8 mL (26 mmol) of 1-(trimethylsilyl)propyne and 3.9 mL (26 mmol) of dry 1,2-bis(dimethylamino)ethane (TMEDA) in 70 mL of anhydrous THF at 0 °C, and stirring was continued for 15 min. After the mixture was cooled to −78 °C, a solution of 4.29 g (21 mmol) of ketone **50a** in 30 mL of dry THF was added by way of a cannula needle, and stirring was continued again for 15 min. The mixture was acidifed with saturated NH_4Cl solution and extracted with ether. The extract was washed with a 5% HCl solution and worked up in the usual manner, leading to 5.76 g of crude, pale yellow oily alcohol **6a**: IR OH 3560 (w), C≡C 2180 (m) cm^{-1}; ^1H NMR δ 0.16 (s, 9, $SiMe_3$), 0.7–1.0 (m, 6, *i*-Pr methyls), 0.98 (s, 3, Me), 2.65 (s, 1, H-5), 2.66, 3.21 (d, 1 each, J = 18 Hz, propargyl Hs), 3.61 (s, 1, H-7).

A solution of the above alcohol in 200 mL of THF and 21.4 mL of a 1 M tetra-*n*-butylammonium fluoride (Bu_4NF) solution was stirred at room temperature for 1 h. The mixture was diluted with ether and subjected to the usual workup. Silica B chromatography of the crude product and elution with 25:1 hexane–EtOAc and subsequent Kugelrohr distillation (74 °C/0.5 Torr) led to 3.85 g (75% overall yield) of colorless, liquid alcohol **6c**: IR OH 3570 (m), ≡CH 3320 (m), C≡C 2125 (w) cm^{-1}; ^1H NMR δ 0.87, 0.94 (d, 3 each, J = 6 Hz, *i*-Pr methyls), 0.96 (s, 3, Me), 2.10 (t, 1, J = 3 Hz, acetylenic H), 2.67 (s, 1, H-5), 2.69, 3.21 (dd, 1 each, J = 17, 3 Hz, propargyl Hs), 3.64 (s, 1, H-7); ^{13}C NMR δ 15.6 (Me), 20.9, 21.5 (*i*-Pr methyls), 22.6 (C-3), 28.8 (propynyl C-1), 33.7 (*i*-Pr CH), 36.6 (C-2), 49.0 (C-1), 50.9 (C-4), 51.8 (C-5), 66.0 (C-7), 71.7 (propynyl C-3), 75.4 (C-6), 80.7 (propynyl C-2). Anal. Calcd for $C_{14}H_{21}OCl$: C, 69.84; H, 8.79. Found: C, 70.18; H, 9.14.

The above reaction of the organolithium reagent [9.54 mL of 0.36 M hexane solution of *n*-butyllithium, 0.51 mL (3.4 mmol) of 1-(trimethylsilyl)propyne, 0.52 mL (3.4 mmol) of TMEDA, and 20 mL of dry THF] with ketone **5b** (732 mg (3.0 mmol), 20 mL of dry THF) yielded 1.09 g of crude, oily alcohol **6b**: ^1H NMR δ 0.15 (s, 9, $SiMe_3$), 0.7–1.0 (m, 6, *i*-Pr methyls), 0.92 (s, 3, Me), 2.70, 3.33 (d, 1 each, J = 18 Hz, propargyl Hs), 2.73 (s, 1, H-5), 3.73 (s, 1, H-7). Desilylation as above (3.43 mL of 1 M THF solution of Bu_4NF, alcohol **6b** in 30 mL of THF), silica B chromatography of the crude product, elution with 4:1 hexane–$CHCl_3$, and Kugelrohr distillation (80 °C/0.3 Torr) gave 621 mg (72% overall yield) of colorless, liquid alcohol **6d**, which crystallized on refrigeration: mp 38–39 °C; IR OH 3570 (m), ≡CH 3320 (m), C≡C 2125 (w) cm^{-1}; ^1H NMR δ 0.87 (s, 3, Me), 0.87, 0.93 (d, 3 each, J = 6 Hz, *i*-Pr methyls), 2.11 (t, 1, J = 3 Hz, acetylenic H), 2.73, 3.33 (dd, 1 each, J = 17, 3 Hz, propargyl Hs), 2.76 (s, 1, H-5), 3.76 (s, 1, H-7); ^{13}C NMR δ 17.8 (Me), 20.9, 21.6 (*i*-Pr methyls), 22.6 (C-3), 28.9 (propynyl C-1), 33.8 (*i*-Pr CH), 36.6 (C-2), 49.0 (C-1), 51.5 (C-4), 52.0 (C-5), 58.8 (C-7), 71.9 (propynyl C-3), 75.5 (C-6), 80.7 (propynyl C-2). Anal. Calcd for $C_{14}H_{21}OBr$: C, 58.96; H, 7.42. Found: C, 58.88; H, 7.32.

1-Methyl-4(*S)-isopropyl-6(*R**)-(2-propenyl)-7(*R**)-chlorobicyclo[3.1.1]heptan-6-ol (8b).** A solution of 132 mg (0.55 mmol) of chloride **6c**, 0.15 mL (0.58 mmol) of tri-*n*-butyltin hydride (Bu_3SnH),[44] and ca. 20 mg azobis(isobutyronitrile) (AIBN) in 12 mL of anhydrous benzene was refluxed for 2 h. Evaporation of the solvent yielded crude, liquid stannane **8a**: IR OH 3550 (w), C=C 1590 (w) cm^{-1}; ^1H NMR δ 0.7–1.0 (m, 15, *i*-Pr and *n*-Bu methyls), 0.94 (s, 3, Me), 1.1–1.9 (m, 2, methylenes, methines), 2.2–2.6 (m, 1, allyl H), 2.62 (s, 1, H-5), 3.30 (dd, 1, J = 15, 3 Hz, allyl H), 3.61 (s, 1, H-7), 6.0–6.2 (m, 2, olefinic Hs). A solution of the crude material and 49 mg (0.31 mmol) of *p*-toluenesulfinic acid in 3 mL of acetonitrile and 60 μL of water was stirred and refluxed for 3 h. More (49 mg, 0.31 mmol) *p*-toluenesulfinic acid was added and refluxing continued for 1 h. Vacuum evaporation of the solvent, filtration of a hexane solution of the residue through a short silica A column, and evaporation of the filtrate gave a residue, whose MPLC and elution with 50:1 hexane–EtOAc led to 53 mg (40%) of colorless, liquid olefin **8b**: IR OH 3560 (m), =CH 3080 (w), C=C 1638 (m) cm^{-1}; ^1H NMR δ 0.85, 0.88 (d, 3 each, J = 6 Hz, *i*-Pr methyls), 0.97 (s, 3, Me), 2.40 (dd, 1, J = 14, 9, Hz, allyl H), 2.61 (s, 1, H-5), 3.16 (ddt, 1, J = 14, 6, 1 Hz, allyl H), 3.63 (s, 1, H-7), 5.2–5.3, 5.8–6.0 (m, 3 total, vinyl Hs); exact mass *m/e* 242.1457 (calcd for $C_{14}H_{23}OCl$ 242.1435).

6-Hydroxy-5-nor-β-copaene (7b). A solution 5.76 g of the above crude chloro acetylene **6a**, 6.8 mL (26 mmol) of Bu_3SnH, and 700 mg (4.3 mmol) of AIBN in 105 mL of anhydrous benzene was refluxed for 58 h. Throughout this period 12 additions of a total of 900 mg (5.5 mmol) of AIBN and 4 additions of a total of 6.5 mL (25 mmol) of Bu_3SnH were made. Vacuum removal of the solvent produced a colorless, liquid mixture of **7b** stereoisomers: IR (each isomer) OH 3605 (m), 3460 (br m), C=C 1643 (m) cm^{-1}; ^1H NMR δ (one isomer) 0.10 (s, 9, $SiMe_3$), 0.80 (s, 3, Me), 0.8–0.9 (m, 6, *i*-Pr methyls), 1.96 (s, 1, H-2), 2.06 (s, 1, H-7), 2.1–2.3 (m, 2, C-4 Hs), 5.16 (t, 1, J = 1 Hz, vinyl H); ^1H NMR

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δ (other isomer) 0.05 (s, 9, $SiMe_3$), 0.80 (s, 3, Me), 0.8–1.0 (m, 6, *i*-Pr methyls), 2.10 (s, 1, H-7), 2.15 (s, 1, H-2), 2.2–2.4 (m, 2, C-4 Hs), 5.0–5.1 (m, 1, vinyl H).

A solution of the above product **7b** and 2.7 g (17 mmol) of *p*-toluenesulfinic acid in 100 mL of acetonitrile and 2 mL of water was refluxed for 5 h. During this period, more *p*-toluenesulfinic acid (1.0 g after 2 h and 0.5 g after 4 h) was added. The suspension was filtered through Celite and the resultant filtrate evaporated. A solution of the residue in 250 mL of hexane was washed with 10% $NaHCO_3$ solution and then worked up in the usual manner. Silica A chromatography of the crude product and elution with hexane removed the organotin substances. Elution with 30:1 hexane–EtOAc yielded 1.62 g of the desired product and ca. 3 g of impure oil. MPLC of the latter and elution with 30:1 hexane–EtOAc led to 1.55 g of material. Kugelrohr distillation (90 °C/0.2 Torr) of the combined fractions furnished 2.86 g (65% **6a** → **7a** overall yield) of colorless, liquid alcohol **7a**: IR OH 3615 (m), 3470 (br w), =CH 3080 (w), C=C 1673 (m), R_2C=CH_2 870 (m) cm^{-1}; ^1H NMR δ 0.83 (s, 3, Me), 0.90, 0.92 (d, 3 each, J = 7 Hz, *i*-Pr methyls), 1.5–1.9 (m, 6, methylenes, methines), 1.88 (s, 1, OH), 2.03 (s, 1, H-2), 2.10 (s, 1, H-7), 2.23, 2.31 (dt, 1 each, J = 14, 2 Hz, C-4 Hs), 4.61, 4.77 (br s, 1 each, olefinic Hs); ^{13}C NMR δ 17.4 (Me), 20.1, 20.4 (*i*-Pr methyls), 22.4 (C-9), 29.5 (C-10), 32.4 (*i*-Pr CH), 39.7 (C-4), 41.3 (C-8), 51.2 (C-1), 55.7 (C-7), 56.3 (C-2), 79.1 (C-6), 101.4 (olefinic CH_2), 149.7 (C-3). Anal. Calcd for $C_{14}H_{22}O$: C, 81.50; H, 10.75. Found: C, 81.72; H, 10.75.

A solution of 605 mg (2.1 mmol) of bromoalkyne **6d**, 0.65 mL (2.4 mmol) of Bu_3SnH, and ca. 20 mg of AIBN in 30 mL of anhydrous benzene was refluxed for 1.5 h and then cooled and evaporated. Silica B chromatography of the residue and elution with 25:1 hexane–EtOAc led to 361 mg of material, whose Kugelrohr distillation (70 °C/0.3 Torr) afforded 355 mg (81%) of colorless, liquid alcohol **7a**, spectrally identical with the above sample.

5-Nor-β-copaene (9b). A 1.28 M hexane solution of *tert*-butyllithium (10.8 mL, 13.9 mmol) was added dropwise to a stirring solution of 2.86 g (13.9 mmol) of alcohol **7a** in 80 mL of anhydrous THF at 0 °C. Thereupon 1.92 mL (13.9 mmol) of phenyl chlorothionocarbonate was added dropwise and the stirring continued at 0 °C for 5 min. The mixture was diluted with ether and then processed in the usual manner. Silica A chromatography of the crude product and elution with 9:1 hexane–CH_2Cl_2 gave 4.37 g (92%) of the pale yellow, liquid ester **9a**: IR =CH 3080 (w), C=C 1675 (m), 1595 (m), C=S 1300 (m), 1250 (m), 1200 (m), R_2C=CH_2 880 (m) cm^{-1}; ^1H NMR δ 0.86, 0.90 (d, 3 each, J = 7 Hz, *i*-Pr methyls), 0.90 (s, 3, Me), 1.0–2.0 (m, 6, methylenes, methines), 2.10 (s, 1, H-2), 2.49, 3.30 (br d, 1 each, J = 14 Hz, C-4 Hs), 2.82 (s, 1, H-7), 4.69, 4.83 (br s, 1 each, olefinic Hs), 7.0–7.2 (m, 5, Ar Hs).

A solution of 208 mg (0.61 mmol) of ester **9a**, 0.53 mL (2.0 mmol) of Bu_3SnH, and 30 mg (0.18 mmol) of AIBN in 10 mL of anhydrous cumene was added dropwise (by way of a syringe pump injector) over a 1.5-h period to 50 mL of anhydrous, refluxing cumene, and thereafter the heating was continued for 1 h. The solution was cooled to 80 °C, 2 mL of absolute CCl_4 added, and the mixture stirred at this temperature for 1 h. Thereupon it was evaporated and the residue exposed to MPLC. Elution with 50:1 hexane–CH_2Cl_2 gave 48 mg of material, whose Kugelrohr distillation produced 29 mg (25%) of colorless liquid olefin **9b**: IR =CH 3070 (w), C=C 1670 (m), R_2C=CH_2 870 (m) cm^{-1}; ^1H NMR δ 0.77 (s, 3, Me), 0.86, 0.87 (d, 3 each, J = 7 Hz, *i*-Pr methyls), 1.5–1.8 (m, 6, methylenes, methines), 1.68 (s, 1, H-7), 2.14, 2.30 (ddd, 1 each, J = 15, 2, 2 Hz, C-4 Hs), 2.20 (br d, 1, J = 7 Hz, H-6), 2.26 (d, 1, J = 7 Hz, H-2), 4.69, 4.92 (br s, 1 each, olefinic Hs); ^{13}C NMR δ 19.3, 19.6 (*i*-Pr methyls), 20.3 (Me), 22.9 (C-9), 31.6 (C-10), 32.2 (*i*-Pr CH), 33.8 (C-4), 40.0 (C-8), 41.2 (C-7), 48.1 (C-1), 51.8 (C-6), 62.9 (C-2), 100.8 (olefinic CH_2), 152.9 (C-3); exact mass m/e 190.1711 (calcd for $C_{14}H_{22}$ 190.1701).

Elution with 100:1 hexane–EtOAc gave first 2 mg (1%) of colorless, liquid acetal **9e**: IR =CH 3080 (w), C=C 1675 (m), 1602 (m), 1592 (m), R_2C=CH_2 878 (m) cm^{-1}; ^1H NMR δ 0.7–1.0 (m, 6, *i*-Pr methyls), 0.88 (s, 3, Me), 1.1–1.7 (m, 6, methylenes, methines), 1.93 (s, 1, H-2), 2.13 (s, 1, H-7), 2.20, 2.60 (dt, 1 each, J = 14, 2 Hz, C-4 Hs), 4.60, 4.73 (br s, 1 each, olefinic Hs), 5.17, 5.23 (d, 1 each, J = 14 Hz, O_2CH_2 Hs), 6.9–7.3 (m, 5, Ar Hs); exact mass m/e 312.2095 (calcd for $C_{21}H_{28}O_2$ 312.2089).

Further elution led to 21 mg (14%) of colorless, liquid mercaptan **9c**: IR =CH 3080 (w), SH 2590 (w), C=C 1675 (m), R_2C=CH_2 880 (m) cm^{-1}; ^1H NMR δ (CD_2Cl_2) 0.87, 0.90 (d, 3 each, J = 6 Hz, *i*-Pr methyls), 0.90 (s, 3, Me), 1.3–1.9 (m, 6, methylenes, methines), 1.97 (s, 1, H-2), 2.17 (s, 1, H-7), 2.19 (t, 1, J = 9 Hz, SH), 2.30, 2.52 (dt, 1 each, J = 14, 2 Hz, C-4 Hs), 4.63, 4.77 (br s, 1 each, olefinic Hs), 4.64, 4.72 (dd, 1 each, J = 11, 9 Hz, OCH_2S); ^{13}C NMR δ (CD_2Cl_2) [δ(Me_4Si) = δ(CD_2Cl_2) + 53.8 ppm] 19.0 (Me), 20.7, 20.9 (*i*-Pr methyls), 23.4 (C-9), 31.0 (C-10), 33.1 (*i*-Pr CH), 35.8 (C-4), 42.4 (C-8), 51.5 (C-1), 54.2 (C-7), 56.5 (C-2), 62.8 (SCH_2), 84.1 (C-6), 101.1 (olefinic CH_2), 149.7 (C-3); exact mass m/e 252.1542 (calcd for $C_{15}H_{24}OS$ 252.1547).

Finally, further elution furnished 20 mg (15%) of colorless, liquid ether **9d**: IR =CH 3080 (w), C=C 1675 (w), R_2C=CH_2 880 (m) cm^{-1}; ^1H NMR δ 0.87, 0.91 (d, 3 each, J = 6 Hz, *i*-Pr methyls), 0.90 (s, 3, Me), 1.4–1.9 (m, 6, methylenes, methines), 1.94 (s, 1, H-2), 2.15 (s, 1, H-7), 2.25, 2.38 (dt, 1 each, J = 14, 2 Hz, C-4 Hs), 3.27 (s, 3, OMe), 4.62, 4.77 (br s, 1 each, olefinic Hs). Anal. Calcd for $C_{15}H_{24}O$: C, 81.76; H, 10.98. Found: C, 81.41; H, 10.79.

3-Demethylene-3-oxo-5-nor-β-copaene (11). Ozone was bubbled through a solution of 194 mg (1.0 mmol) of olefin **9b** in 10 mL of dry methanol at −30 °C until all of the starting olefin had been consumed (TLC analysis). Nitrogen was bubbled through the mixture for 10 min, 39 mg (0.5 mmol) of thiourea[45] was added, and the solution was stirred at room temperature for 1 h. The resultant precipitate was filtered and discarded and the filtrate evaporated. MPLC of the residue and elution with 30:1 hexane–EtOAc gave 70 mg (33%) of colorless, liquid ketone **11**: IR C=O 1755 (s) cm^{-1}; ^1H NMR δ 0.88, 0.90 (d, 3 each, J = 6 Hz, *i*-Pr methyls), 0.90 (s, 3, Me), 1.5–1.9 (m, 6, methylenes, methines), 2.08 (s, 1, H-7), 2.11, 2.37 (br d, 1 each, J = 16 Hz, C-4 Hs), 2.33 (d, 1, J = 7 Hz, H-6), 2.50 (d, 1, J = 7 Hz, H-2); ^{13}C NMR δ 19.2, 19.4 (*i*-Pr methyls), 20.9 (Me), 21.9 (C-9), 31.2 (C-10), 31.6 (*i*-Pr CH), 38.7 (C-8), 39.2 (C-7), 40.6 (C-4), 50.1 (C-1), 50.9 (C-6), 68.6 (C-2), 213.6 (C-3); exact mass m/e 192.1521 (calcd for $C_{13}H_{20}O$ 192.1529).

3,7aβ-Dimethyl-5-isopropyl-3aβ,4,5β,6,7,7aβ-hexahydroinden-1-one (12). A freshly prepared, 1 M 1,3-diaminopropane solution of its potassium monoamide (40 μL) was added to a solution of 75 mg (0.36 mmol) of alcohol **7a** in 1 mL of dry 1,3-diaminopropane, and the mixture was stirred at room temperature for 45 h (after 10 min the solution became red in color). Water and ether were added, and the aqueous layer was extracted with ether. The combined ether solutions were processed in the usual manner. Silica B chromatography of the crude product and elution with 30:1 hexane–EtOAc gave 56 mg (75%) of colorless, liquid ketone **12**: IR =CH 3075 (w), C=O 1710 (s), C=C 1625 (m) cm^{-1}; ^1H NMR δ 0.85, 0.86 (d, 3 each, J = 7 Hz, *i*-Pr methyls), 1.09 (s, 3, Me), 1.1–2.0 (m, 8, methylenes, methines), 2.09 (s, 3, 3-Me), 2.33 (dd, 1, J = 12, 6 Hz, H-3aβ), 5.78 (s, 1, H-2); ^{13}C NMR δ 17.4 (C-6), 19.2, 19.6 (*i*-Pr methyls), 23.4 (7aβ-Me), 25.1 (*i*-Pr CH), 29.2 (3-Me), 30.9 (C-4), 32.7 (C-5), 39.7 (C-7), 47.6 (C-7a), 53.2 (C-3a), 126.3 (C-2), 179.9 (C-3), 213.8 (C-1); exact mass m/e 206.1673 (calcd for $C_{14}H_{22}O$ 206.1669).

4-(*p*-Tolylsulfonyl)-1-(trimethylsilyl)-1-butyne (13b). A mixture of 21.79 g (0.14 mmol) of chloride **13a**, 27.68 g (0.16 mmol) of anhydrous solution *p*-toluenesulfinate, and 20.33 g (0.13 mmol) of anhydrous NaI in 135 mL of dry DMF was stirred at 80 °C for 10 h and then at 40 °C for 12 h. The solution was cooled, diluted with water, and extracted with ether. The usual workup gave a crude solid whose crystallization from ether yielded 18.58 g of crystals. Crystallization from 1:1 hexane–Et_2O of the residue of evaporation of the mother liquor furnished a second crop (4.83 g) of the crystals, thus leading to 23.41 g (62%) of colorless, crystalline sulfone **13b**: mp 108–110 °C; IR C≡C 2180 (m), C=C 1598 (m), SO_2 1320 (m), 1155 (m) cm^{-1}; ^1H NMR δ 0.10 (s, 9, $SiMe_3$), 2.43 (s, 3, Me), 2.5–2.7 (m, 2, C-3 Hs), 3.1–3.4 (m, 2, C-4 Hs), 7.32 (d, 2, J = 8 Hz, meta Hs), 7.75 (d, 2, J = 8 Hz, ortho Hs). Anal. Calcd for $C_{14}H_{20}O_2SSi$: C, 59.96; H, 7.19. Found: C, 59.78; H, 7.31.

7(*R)-Chloro-1-methyl-4(*S**)-isopropylbicyclo[3.1.1]heptan-6(*R**)-ol (14).** A freshly prepared 0.235 M ethereal solution of the **13a** Grignard reagent (4.02 mL, 0.95 mmol) was added dropwise to a stirring solution of 158 mg (0.79 mmol) of ketone **5a** in 0.5 mL of dry ether, and the mixture was refluxed for 2 h. The cooled solution was acidified with saturated NH_4Cl solution and extracted with ether. The usual workup of the extract, silica B chromatography of the crude product, and elution with 25:1 hexane–EtOAc provided 110 mg (69%) of colorless, liquid alcohol **14** (Kugelrohr distillation (70 °C/0.05 Torr) furnished the analytically pure sample): IR OH 3630 (m), 3480 (br w) cm^{-1}; ^1H NMR δ 0.88, 0.93 (d, 3 each, J = 6 Hz, *i*-Pr methyls), 1.10 (s, 3, Me), 1.6–2.1 (m, 6, methylenes, methines), 2.73 (d, 1, J = 6 Hz, H-5), 3.54 (s, 1, H-7), 4.30 (d, 1, J = 6 Hz, H-6); ^{13}C NMR δ 19.8 (Me), 21.0, 21.1 (*i*-Pr methyls), 22.4 (C-3), 33.1 (*i*-Pr CH), 33.6 (C-2), 48.3 (C-4), 49.4 (C-1), 50.1 (C-5), 66.1 (C-7), 72.4 (C-6); exact mass m/e 167.1426 (calcd for $C_{11}H_{19}OCl$ 167.1435). Anal. Calcd for $C_{11}H_{19}OCl$: C, 65.17; H, 9.45. Found: C, 65.40; H, 9.82.

Additions of Ketones 5 and Lithiated Sulfone 15. A 1.5 M hexane solution of *n*-butyllithium (1.81 mL, 2.7 mmol), was added dropwise to a stirring solution of 789 mg (2.8 mmol) of sulfone **13b** in 25 mL of dry THF at −78 °C, and the stirring was continued for 15 min. A solution

(45) Dev, S.; Gupta, D.; Soman, R. *Tetrahedron* **1982**, *38*, 3013.

of 491 mg (2.5 mmol) of ketone **5a** in 7 mL of dry THF was added through a cannula needle, and the mixture was stirred at the low temperature for 1.5 h. A saturated NH_4Cl solution was added to the suspension, and the aqueous layer was extracted with ether. The combined organic solutions were processed in the usual fashion, and the crude product was subjected to MPLC. Elution with 25:1 hexane–EtOAc yielded 17 mg of recovered ketone **5a** and 189 mg (17%, based on consumed ketone **5a**) of colorless, crystalline 7(*R**)-chloro-1-methyl-4-(*S**)-isopropyl-6(*R**)-[1*S**-(*p*-tolylsulfonyl)-4-(trimethylsilyl)-3-butynyl]bicyclo[3.1.1]heptan-6-ol (**16b**): mp 112–114 °C (hexane); IR OH 3500 (m), C≡C 2180 (m), C=C 1600 (m), SO_2 1140 (s) cm^{-1}; ^1H NMR δ 0.01 (s, 9, $SiMe_3$), 0.9–1.0 (m, 6, *i*-Pr methyls), 1.10 (s, 3, Me), 1.6–2.0 (m, 6, methylenes, methines), 2.46 (s, 3, aryl Me), 2.56 (d, 1, *J* = 6 Hz, butynyl H-2), 2.65 (d, 1, *J* = 2 Hz, butynyl H-2), 3.60 (s, 1, OH), 3.69 (s, 1, H-7), 3.88 (s, 1, H-5), 4.51 (dd, 1, *J* = 6, 2 Hz, butynyl H-1), 7.34 (d, 2, *J* = 8 Hz, meta Hs), 7.83 (d, 2, *J* = 8 Hz, ortho Hs). Anal. Calcd for $C_{25}H_{37}O_3ClSSi$: C, 62.41; H, 7.75. Found: C, 62.32; H, 7.63.

Further elution afforded 812 mg (72%, based on consumed ketone **5a**) of colorless, crystalline 7(*R**)-chloro-1-methyl-4(*S**)-isopropyl-6(*R**)-[1(*R**)-(*p*-tolylsulfonyl)-4-(trimethylsilyl)-3-butynyl]bicyclo[3.1.1]heptan-6-ol (**16a**): mp 91–94 °C (hexane); IR OH 3510 (m), C≡C 2180 (m), C=C 1600 (m), SO_2 1145 (s) cm^{-1}; ^1H NMR δ 0.10 (s, 9, $SiMe_3$), 0.86, 0.95 (d, 3 each, *J* = 6 Hz, *i*-Pr methyls), 1.28 (s, 3, Me), 1.5–2.0 (m, 6, methylenes, methines), 2.45 (s, 3, aryl Me), 2.86 (d, 2, *J* = 5 Hz, butynyl C-2 Hs), 2.94 (s, 1, H-5), 3.58 (s, 1, OH), 3.63 (s, 1, H-7), 4.37 (t, 1, *J* = 5 Hz, butynyl H-1), 7.32 (d, 2, *J* = 9 Hz, meta Hs), 7.85 (d, 2, *J* = 9 Hz, ortho Hs). Anal. Calcd for $C_{25}H_{37}O_3ClSSi$: C, 62.41; H, 7.75. Found: C, 62.20; H, 7.96.

The above **5a** → **16** reaction procedure was repeated for the reaction of **5b** (except the addition process lasted for 4 h instead of 1.5 h), utilizing 21.7 mL (56.5 mmol) of a 2.6 M hexane solution of *n*-butyllithium, 16.6 g (59.1 mmol) of sulfone **13b** in 250 mL of dry THF, and 13.1 g (53.8 mmol) of ketone **5b** in 30 mL of dry THF. Silica A chromatography of the crude product and elution with 25:1 hexane–EtOAc yielded fractions of individual sulfones and 5 g of their mixture. MPLC of the latter and elution with 15:1 hexane–EtOAc partitioned the material into its two components. Crystallization of the major constituent from hexane furnished 20.4 g (72%) of colorless, crystalline 7(*R**)-bromo-1-methyl-4-(*S**)-isopropyl-6(*R**)-[1(*R**)-(*p*-tolylsulfonyl)-4-(trimethylsilyl)-3-butynyl]bicyclo[3.1.1]heptan-6-ol (**27a**): mp 107–110 °C; IR OH 3500 (m), C≡C 2180 (m), C=C 1600 (m), SO_2 1140 (m) cm^{-1}; ^1H NMR δ 0.10 (s, 9, $SiMe_3$), 0.86, 0.96 (d, 3 each, *J* = 6 Hz, *i*-Pr methyls), 1.29 (s, 3, Me), 1.7–2.0 (m, 6, methylenes, methines), 2.45 (s, 3, aryl Me), 2.85 (dd, 1, *J* = 20, 4 Hz, butynyl H-2), 2.93 (dd, 1, *J* = 20, 6 Hz, butynyl H-2), 3.02 (s, 1, H-5), 3.60 (s, 1, OH), 3.77 (s, 1, H-7), 4.53 (dd, 1, *J* = 6, 4 Hz, butynyl H-1), 7.35 (d, 2, *J* = 8 Hz, meta, Hs), 7.87 (d, 2, *J* = 8 Hz, ortho Hs); ^{13}C NMR δ −0.4 ($SiMe_3$), 18.7 (butynyl C-2), 21.2 (Me), 21.6 (aryl Me), 22.0, 22.7 (*i*-Pr methyls), 22.8 (C-3), 32.8 (*i*-Pr CH), 37.4 (C-2), 51.1 (C-1), 51.3 (C-4), 53.3 (C-5), 60.3 (C-7), 69.2 (butynyl C-1), 81.0 (C-6), 88.6 (butynyl C-4), 102.2 (butynyl C-3), 129.0 (*m*-C), 129.7 (*o*-C), 137.2 (*p*-C), 144.6 (*ipso*-C). Anal. Calcd for $C_{25}H_{37}O_3BrSSi$: C, 57.13; H, 7.10. Found: C, 57.16; H, 7.34.

Crystallization of the minor constitutent from hexane afforded 2.69 g (10%) of colorless, crystalline 7(*R**)-bromo-1-methyl-4(*S**)-isopropyl-6(*R**)-[1(*S**)-(*p*-tolylsulfonyl)-4-(trimethylsilyl)-3-butynyl]bicyclo[3.1.1]heptan-6-ol (**27b**): mp 128–129 °C; IR OH 3510 (m), C≡C 2180 (m), C=C 1600 (m), SO_2 1140 (s) cm^{-1}; ^1H NMR δ 0.00 (s, 9, $SiMe_3$), 0.91, 1.09, (d, 3 each, *J* = 6 Hz, *i*-Pr methyls), 1.11 (s, 3, Me), 1.7–2.4 (m, 6, methylenes, methines), 2.45 (s, 3, aryl Me), 2.54 (dd, 1, *J* = 20, 8 Hz, butynyl H-2), 2.75 (dd, 1, *J* = 20, 1 Hz, butynyl H-2), 3.61 (s, 1, OH), 3.84 (s, 1, H-7), 4.00 (s, 1, H-5), 4.71 (dd, 1, *J* = 8, 1 Hz, butynyl H-1), 7.33 (d, 2, *J* = 8 Hz, meta Hs), 7.80 (d, 2, *J* = 8 Hz, ortho Hs); ^{13}C NMR δ −0.3 ($SiMe_3$), 19.1 (butynyl C-2), 20.5 (Me), 21.3, 21.7 (*i*-Pr methyls), 21.6 (aryl Me), 22.6 (C-3), 33.7 (*i*-Pr CH), 37.2 (C-2), 50.1 (C-4), 51.5 (C-1), 52.6 (C-5), 59.2 (C-7), 68.9 (butynyl C-1), 79.8 (C-6), 85.9 (butynyl C-4), 102.7 (butynyl C-3), 129.2 (*m*-C), 129.8 (*o*-C), 135.4 (*p*-C), 144.9 (*ipso*-C). Anal. Calcd for $C_{25}H_{37}O_3BrSSi$: C, 57.13; H, 7.10. Found: C, 57.20; H, 7.21.

The use of excess butyllithium in the **13b** → **15** reaction and the interaction of the mixture with ketone **5a** led to a new material, whose Kugelrohr distillation (105 °C/0.1 Torr) yielded colorless, liquid 7-(*R**)-chloro-1-methyl-4(*S**)-isopropyl-6(*R**)-[4-(trimethylsilyl)-2-buten-3-ynyl]bicyclo[3.1.1]heptan-6-ol (**31a**): IR OH 3600 (m), 3510 (br w), =CH 3060 (w), C≡C 2155 (m), C=C 1620 (w), (*E*)-CH=CH 963 (m) cm^{-1}; ^1H NMR δ 0.23 (s, 9, $SiMe_3$), 0.8–1.0 (m, 6, *i*-Pr methyls), 0.96 (s, 3, Me), 1.43 (s, 1, OH), 1.5–2.3 (m, 6, methylenes, methines), 2.71 (s, 1, H-5), 3.68 (s, 1, H-7), 5.83 (d, 1, *J* = 17 Hz, butenynyl H-2), 7.03 (d, 1, *J* = 17 Hz, butenynyl H-1); exact mass (M − Cl) *m/e* 289.1995 (calcd for $C_{18}H_{29}OClSi$ 289.1985). Anal. Calcd for $C_{18}H_{29}OClSi$: C, 66.53; H, 8.99. Found: C, 66.37; H, 9.05.

Excess *n*-butyllithium in the preparation of organolithium reagent **15** and subsequent interaction with ketone **5b** or exposure of 2 equiv of BuLi to sulfone **27a** or **27b** led to colorless, liquid 7(*R**)-bromo-1-methyl-4-(*S**)-isopropyl-6(*R**)-[4-(trimethylsilyl)-2-buten-3-ynyl]bicyclo[3.1.1]-heptan-6-ol (**31b**): IR OH 3600 (m), 3510 (br m), C≡C 2180 (m), C=C 1620 (w), (*E*)-CH=CH 962 (m) cm^{-1}; ^1H NMR δ 0.20 (s, 9, $SiMe_3$), 0.7–1.0 (m, 6, *i*-Pr methyls), 0.93 (s, 3, Me), 1.43 (s, 1, OH), 1.5–2.3 (m, 6, methylenes, methines), 2.76 (s, 1, H-5), 3.73 (s, 1, H-7), 5.80 (d, 1, *J* = 16 Hz, butenynyl H-2), 7.05 (d, 1, *J* = 16 Hz, butenynyl H-1).

7(*R)-Chloro-1-methyl-4(*S**)-isopropyl-6(*R**)-[4-(trimethylsilyl)-3-butynyl]bicyclo[3.1.1]heptan-6-ol (17) and 7(*R**)-Chloro-1-methyl-4-(*S**)-isopropyl-6-[4-(trimethylsilyl)-3-butynylidene]bicyclo[3.1.1]heptane (18).** Dry methanol (14 mL) was added to a solution of 812 mg (1.7 mmol) of sulfone **16a** in 3 mL of anhydrous THF, and the combined solution was cooled to −20 °C. Anhydrous Na_2HPO_4 (1.44 g, 10.1 mmol) and subsequently 3.9 g (10.1 mmol) of 6% sodium amalgam were added, and the mixture was stirred vigorously at this temperature for 0.5 h. The supernatant liquid was decanted from the precipitate and poured into a water–ether mixture. The aqueous layer was washed with ether, and all of the ether solutions were combined and submitted to the usual workup. MPLC of the crude product and elution with 30:1 hexane–EtOAc led to 183 mg (35%) of a colorless, liquid, ca. 2:1 *E–Z* isomer mixture of chlorides **18**: IR C≡C 2180 (m), C=C 1705 (w) cm^{-1}; ^1H NMR δ (*E* isomer) 0.73, 0.83 (d, 3 each, *J* = 7 Hz, *i*-Pr methyls), 0.94 (s, 3, Me), 1.2–2.0 (m, 6, methylenes, methines), 2.7–2.8 (m, 2, butynylidene C-2 Hs), 2.93 (s, 1, H-5), 3.55 (s, 1, H-7), 5.15 (t, 1, *J* = 7 Hz, olefinic H), δ (*Z* isomer) 0.73, 0.75 (d, 3 each, *J* = 7 Hz, *i*-Pr methyls), 1.14 (s, 3, Me), 1.2–2.0 (m, 6, methylenes, methines), 2.64 (s, 1, H-5), 2.82, 2.84 (d, 1 each, *J* = 7 Hz, butynylidene C-2 Hs), 3.52 (s, 1, H-7), 5.22 (t, 1, *J* = 7 Hz, olefinic H); exact mass *m/e* 308.1723 (calcd for $C_{18}H_{29}ClSi$ 308.1721).

Further elution led to 272 mg (49%) of colorless, liquid alcohol **17** (Kugelrohr distillation (95 °C/0.1 Torr) yielding the analytically pure sample): IR OH 3530 (m), C≡C 2175 (m) cm^{-1}; ^1H NMR δ 0.16 (s, 9, $SiMe_3$), 0.73, 0.81 (d, 3 each, *J* = 6 Hz, *i*-Pr methyls), 0.81 (s, 3, Me), 1.5–1.8 (m, 6, methylenes, methines), 1.9–2.1 (m, 2, butynyl C-1 Hs), 2.3–2.5 (m, 2, butynyl C-2 Hs), 2.51 (s, 1, H-5), 2.77 (s, 1, OH), 3.48 (s, 1, H-7); ^{13}C NMR δ −0.2 ($SiMe_3$), 14.2 (butynyl C-2), 15.3 (Me), 21.3, 21.5 (*i*-Pr methyls), 22.5 (C-3), 33.4 (*i*-Pr CH), 35.0 (butynyl C-1), 36.5 (C-2), 49.7 (C-1), 50.1 (C-4), 51.0 (C-5), 66.4 (C-7), 77.5 (C-6), 86.7 (butynyl C-4), 107.5 (butynyl C-3). Anal. Calcd for $C_{18}H_{31}OClSi$: C, 66.12; H, 9.56. Found: C, 66.43; H, 9.64.

When the desulfonylation was carried out on a **16a–16b** sulfone isomer mixture in methanol solution in the presence of 5 times the above quantity of Na_2HPO_4 and sodium amalgam and added HOAc (1 equiv) at temperatures higher than −20 °C, the reaction yielded alcohol **17** and olefin **18** in 45 and 36% yields, respectively, as well as desilyl-**17**.[46,47]

Free-Radical Cyclizations of Haloalkynes and Desilylation of Olefinic Products. General Procedures for the Cyclization of Chloroalkynes. A solution of 0.50 mmol of chloroalkyne, 0.75 mmol of Bu_3SnH, and 0.10 mmol of AIBN in 16.5 mL of dry benzene was refluxed for 48 h. During this period, more (0.25 mmol each) Bu_3SnH was added at the 16- and 32-h reaction times. Similarly, 0.03-mmol lots of AIBN were added at 8-h intervals. Vacuum evaporation provided the crude dehalogenation products.

General Procedure for the Cyclization of Bromoalkynes. A solution of 0.50 mmol of bromoalkyne, 0.75 mmol of Bu_3SnH, and 0.10 mmol of AIBN in 5 mL of dry benzene was refluxed for 1.5 h. Thereafter 0.50 mmol of Bu_3SnH and 0.08 mmol of AIBN were added and refluxing continued for an additional 1.5 h. Vacuum evaporation provided the crude dehalogenation products.

General Procedure for Desilylation of Trimethylsilylated Olefinic Products. Freshly prepared *p*-toluenesulfinic acid (0.30 mmol) (by aqueous HCl precipitation from the sodio salt) was added to a solution of the crude dehalogenation material in 2.5 mL of acetonitrile and 50 μL of water. The mixture was refluxed for 12 h, during which time (after 3, 6, and 9 h) 0.22-mmol lots of *p*-toluenesulfinic acid were added. The solvent was evaporated under vacuum and the residue dissolved in ether. The solution was washed with 5% $NaHCO_3$ solution and submitted to the general workup. The crude product was chromatographed on silica B, with the early hexane eluates removing all tin byproducts. *It is important to note that utilization of the desilylation procedure on pu-*

(46) Cf. Eisch, J. J.; Gupta, G. *J. Organomet. Chem.* **1979**, *168*, 139.
(47) IR: OH 3550 (m), ≡CH 3310 (m), C≡C 2110 (w) cm^{-1}; ^1H NMR δ 0.82, 0.90 (d, 3 each, *J* = 6 Hz, *i*-Pr methyls), 0.95 (s, 3, Me), 1.5–2.2 (m, 8, methylenes, methines), 2.01 (t, 1, butynyl H-4), 2.2–2.5 (m, 2, butynyl C-2 Hs), 2.61 (s, 1, H-5), 3.60 (s, 1, H-7).

rified, dehalogenated vinylsilanes leads to a mixture of double bond isomers of the desired olefins.

1-Methyl-4(*S)-isopropyl-6(*R**)-[4-(trimethylsilyl)-3-butynyl]bicyclo[3.1.1]heptan-6-ol (19)** (from **17**; early fractions of 25:1 hexane–EtOAc elution): colorless liquid (57%); IR OH 3540 (m), C≡C 2180 (m) cm^{-1}; ^1H NMR δ 0.20 (s, 9, $SiMe_3$), 0.86 (s, 3, Me), 0.86, 0.93 (d, 3 each, J = 6 Hz, *i*-Pr methyls), 1.2–2.0 (m, 10, methylenes, methines), 2.22 (s, 1, OH), 2.3–2.6 (m, 2, butynyl C-2 Hs), 2.40 (br d, 1, 1, J = 6 Hz, H-5); ^{13}C NMR δ –0.5 ($SiMe_3$), 14.1 (butynyl C-2), 18.9 (Me), 20.8, 21.0 (*i*-Pr methyls), 22.5 (C-3), 33.4 (C-1), 33.5 (*i*-Pr CH), 33.9 (C-2), 35.3 (butynyl C-1), 40.4 (C-4), 45.0 (C-7), 47.7 (C-5), 77.1 (C-6), 85.0 (butynyl C-4), 107.4 (butynyl C-3); exact mass m/e 292.2222 (calcd for $C_{18}H_{32}OSi$ 292.2222).

6-Hydroxy-β-copaene (20) (from **17**; later fractions of 25:1 hexane–EtOAc elution; Kugelrohr distillation 70 °C/0.01 Torr): colorless, crystalline solid (32%); mp 34–37 °C; IR OH 3600 (m), 3470 (br m), =CH 3070 (m), C=C 1640 (m), $R_2C{=}CH_2$ 880 (m) cm^{-1}; ^1H NMR δ 0.73 (s, 3, Me), 0.89, 0.92 (d, 3 each, J = 6 Hz, *i*-Pr methyls), 1.5–1.8 (m, 6, methylenes, methines), 1.8–2.0 (m, 2, C-5 Hs), 1.93 (s, 1, H-2), 2.31 (dd, 1, J = 17, 9 Hz, H-4), 2.38 (s, 1, H-7), 2.58 (dddt, 1, J = 17, 11, 8, 3 Hz, H-4), 4.60, 4.65 (br s, 1 each, olefinic Hs); ^{13}C NMR δ 17.2 (Me), 20.8, 21.0 (*i*-Pr methyls), 22.9 (C-9), 25.6 (C-4), 31.5 (C-5), 33.4 (*i*-Pr CH), 33.9 (C-10), 45.8 (C-8), 46.4 (C-7), 47.7 (C-1), 54.4 (C-2), 76.1 (C-6), 106.6 (olefinic CH_2), 148.8 (C-3). Anal. Calcd for $C_{15}H_{24}O$: C, 81.76; H, 10.98. Found: C, 81.93; H, 11.12.

Dry methanol (6 mL) and subsequently anhydrous Na_2HPO_4 (2.81 g, 19.8 mmol) was added to a solution of 1.24 g (3.3 mmol) of sulfone **30** (vide infra) in 12 mL of dry THF, and the temperature was lowered to –20 °C. Sodium amalgam (6%, 7.58 g, 19.8 mmol in Na) was added and the mixture stirred vigorously for 1 h. It then was diluted with ether and water and decanted from the undissolved solid. Workup of the etheral solution, MPLC of the crude product, and elution with 25:1 hexane–EtOAc led to 486 mg (67%) of colorless, liquid alcohol **20**, spectrally identical with the above sample.

1-Methyl-4(*S)-isopropyl-6(*R**)-[4-(trimethylsilyl)-2-buten-3-ynyl]bicyclo[3.1.1]heptan-6-ol (28)** (from **16a**; MPLC; early fractions of 25:1 hexane–EtOAc elution): colorless liquid (24%); IR OH 3600 (m), 3520 (br w), =CH 3035 (w), C≡C 2145 (m), C=C 1620 (w), (*E*)-CH=CH 960 (m) cm^{-1}; ^1H NMR δ 0.22 (s, 9, $SiMe_3$), 0.8–0.9 (m, 6, *i*-Pr methyls), 0.83 (s, 3, Me), 1.1–1.9 (m, 8, methylenes, methines), 1.43 (s, 1, OH), 2.48 (d, 1, J = 7 Hz, H-6), 5.82, 6.55 (d, 1 each, J = 16 Hz, olefinic Hs); exact mass m/e 290.2070 (calcd for $C_{18}H_{30}OSi$ 290.2076).

6-Hydroxy-5(*R)-(*p*-tolylsulfonyl)-β-copaene vinylsilanes 29** (from **16a**; MPLC; later fractions of 25:1 hexane–EtOAc elution): amorphous solid ca. 3:2 stereoisomer mixture (37%): IR OH 3480 (m), C=C 1612 (m), 1598 (m), SO_2 1300 (m), 1140 (m), $R_2C{=}C(R)H$ 840 (m) cm^{-1}; ^1H NMR δ (major isomer) 0.00 (s, 3, $SiMe_3$), 0.66 (s, 3, Me), 0.8–0.9 (m, 6, *i*-Pr methyls), 1.0–3.2 (m, 8, methylenes, methines), 2.00 (s, 1, H-2), 2.43 (s, 3, aryl Me), 2.73 (s, 1, H-7), 3.46 (t, 1, J = 8 Hz, H-5), 4.50 (s, 1, OH), 5.13 (br s, 1, olefinic H), 7.33 (d, 2, J = 7 Hz, meta Hs), 7.76 (d, 2, J = 7 Hz, ortho Hs), δ (minor isomer) 0.03 (s, 9, $SiMe_3$), 0.63 (s, 3, Me), 0.8–0.9 (m, 6, *i*-Pr methyls), 1.0–3.2 (m, 8, methylenes, methines), 2.06 (s, 1, H-2), 2.43 (s, 3, aryl Me), 2.75 (s, 1, H-7), 3.43 (t, 1, J = 8 Hz, H-5), 4.43 (s, 1, OH), 5.06 (br s, 1, olefinic H), 7.33 (d, 2, J = 7 Hz, meta Hs), 7.76 (d, 2, J = 7 Hz, ortho Hs). Dehalogenation of sulfone **27a** liberated enyne **28** (47%) and the sulfone mixture **29** (42%).

6-Hydroxy-5(*R)-(*p*-tolylsulfonyl)-β-copaene (30)** from **32**, prepared in the following manner. A mixture of 200 mg (0.38 mmol) of sulfone **27a** and 0.42 mL of a 1 M THF solution of tetra-*n*-butylammonium fluoride in 4 mL of THF was stirred at room temperature for 1 h. It then was diluted with 50 mL of ether, washed with water and brine, dried, and evaporated. The residual colorless liquid (179 mg) was 7(*R**)-bromo-1-methyl-4(*S**)-isopropyl-6(*R**)-[1(*R**)-(*p*-tolylsulfonyl)-3-butynyl]bicyclo[3.1.1]heptan-6-ol (**32**): IR OH 3500 (br m), ≡CH 3310 (m), C≡C 2120 (w), SO_2 1310 (m), 1140 (m) cm^{-1}; ^1H NMR δ 0.8–1.0 (m, 6, *i*-Pr methyls), 1.26 (s, 3, Me), 1.5–3.5 (m, 6, methylenes, methines), 2.00 (t, 1, J = 2 Hz, C≡CH), 2.45 (s, 3, aryl Me), 2.7–2.9 (m, 2, butynyl C-2 Hs), 2.97 (s, 1, H-5), 3.76 (s, 1, H-7), 4.46 (dd, 1, J = 5, 4 Hz, butynyl H-1), 7.33 (d, 2, J = 7 Hz, meta Hs), 7.85 (d, 2, J = 7 Hz, ortho Hs). **30**: (MPLC; elution with 16:1 hexane–EtOAc; crystallized from hexane and from ether) colorless, crystalline solid; mp 127–130 °C; IR OH 3480 (m), =CH 3070 (w), C=C 1640 (m), 1600 (m), SO_2 1295 (m), 1140 (m), $R_2C{=}CH_2$ 875 (m) cm^{-1}; ^1H NMR δ 0.70 (s, 3, Me), 0.85, 0.90 (d, 3 each, J = 7 Hz, *i*-Pr methyls), 1.5–2.1 (m, 6, methylenes, methines), 1.92 (s, 1, H-2), 2.35 (dd, 1, J = 17, 9 Hz, H-4), 2.45 (s, 3, aryl Me), 2.74 (s, 1, H-7), 2.93 (ddt, 1, J = 17, 9, 3 Hz, H-4), 3.52 (t, 1, J = 9 Hz, H-5), 4.56 (s, 1, OH), 4.63, 4.65 (br s, 1 each, olefinic Hs), 7.37 (d, 2, J = 8 Hz, meta Hs), 7.80 (d, 2, J = 8 Hz, ortho Hs); ^{13}C NMR δ 16.7 (Me), 20.7, 21.0 (*i*-Pr methyls), 21.5 (aryl Me), 22.3 (C-9), 28.8 (C-4), 33.0 (*i*-Pr CH), 34.3 (C-10), 43.4 (C-7), 46.0 (C-8), 49.4 (C-1), 53.2 (C-2), 63.9 (C-5), 77.6 (C-6), 108.1 (olefinic CH_2), 128.6 (*m*-C), 129.8 (*o*-C), 135.4 (*p*-C), 144.3 (*ipso*-C), 144.9 (C-3). Anal. Calcd for $C_{22}H_{30}O_3S$: C, 70.55; H, 8.07. Found: C, 70.48; H, 8.17. Desilylation of olefin **29** liberated olefin **30** (79%).

Enyne **28** (from **27b**; MPLC; early fractions of 25:1 hexane–EtOAc elution): colorless liquid (15%); spectrally identical with the above sample.

1-Methyl-4(*S)-isopropyl-6(*R**)-[1(*S**)-(*p*-tolylsulfonyl)-4-(trimethylsilyl)-3-butynyl]bicyclo[3.1.1]heptan-6-ol (33)** (from **27b**; MPLC; later fractions of 25:1 hexane–EtOAc elution; crystallized from ether): colorless, crystalline solid; mp 138–140 °C; IR OH 3520 (m), C≡C 2180 (m), C=C 1600 (m), SO_2 1135 (m) cm^{-1}; ^1H NMR δ 0.01 (s, 9, $SiMe_3$), 0.86, 1.03 (d, 3 each, J = 6 Hz, *i*-Pr methyls), 0.93 (s, 3, Me), 1.4–2.0 (m, 8, methylenes, methines), 2.40 (dd, 1, J = 18, 7 Hz, butynyl H-2), 2.44 (s, 3, aryl Me), 2.73 (dd, 1, J = 18, 2 Hz, butynyl H-2), 3.57 (br d, 1, J = 7 Hz, H-5), 3.60 (dd, 1, J = 7, 2 Hz, butynyl H-1), 7.33 (d, 2, J = 8 Hz, meta Hs), 7.85 (d, 2, J = 8 Hz, ortho Hs). Anal. Calcd for $C_{25}H_{38}O_3SSi$: C, 67.22; H, 8.57. Found: C, 66.97; H, 8.53.

(±)-β-Copaene (1). A mixture of 250 mg (1.1 mmol) of alcohol **20** and 10 mg of γ-(dimethylamino)pyridine in 2.4 mL (16.8 mmol) of triethylamine and 1.05 mL (11.3 mmol) of acetic anhydride was stirred at room temperature for 24 h. Thereupon 0.43 mL (4.5 mmol) of acetic anhydride was added and the stirring continued for 20 h. The mixture was poured into a 5% HCl solution and extracted with ether. Workup of the extract, MPLC of the crude product, and elution with 30:1 hexane–EtOAc gave the pure product and an impure fraction, whose reexposure to MPLC and elution with 50:1 hexane–EtOAc led to a total of 253 mg (85%) of colorless, liquid 6-acetoxy-β-copaene (**21**): IR =CH 3074 (w), C=O 1734 (s), C=C 1641 (w), $R_2C{=}CH_2$ 884 (m) cm^{-1}; ^1H NMR δ 0.86, 0.93 (d, 3 each, J = 6 Hz, *i*-Pr methyls), 0.89 (s, 3, Me), 1.2–2.0 (m, 7, methylenes, methines), 1.98 (s, 3, acetyl Me), 2.0–2.7 (m, 4, C-4 and C-5 Hs), 2.67 (s, 1, H-7), 4.61, 4.68 (br s, 1 each, olefinic Hs). The product was used directly in the next reaction.

A solution of 250 mg (0.95 mmol) of ester **21** and 0.9 mL of water in 18 mL of purified hexamethylphosphoramide (HMPA) in a quartz tube under nitrogen was irradiated at 254 nm in a Rayonet preparative photochemical reactor for 7 h and then poured into 100 mL of ice water. The mixture was extracted with ether. The resulting ethereal solution was extracted with a 5% $NaHCO_3$ solution and worked up in the usual manner. Silica A chromatography of the crude product and elution with pentane gave the pure, desired hydrocarbon, and further elution with 30:1 hexane–EtOAc led to a **20–21** mixture. MPLC thereof and elution with 30:1 hexane–EtOAc furnished recovered 54 mg of ester **21** and 7 mg of alcohol **20**. The hydrocarbon consisted of 42 mg (29%, based on consumed ester **21**) of colorless, liquid (±)-β-copaene (**1**): IR, ^1H NMR, and ^{13}C NMR spectrally identical with literature citations;[3,48] ^1H NMR (500 MHz) δ 0.69 (s, 3, Me), 0.85, 0.86 (d, 3 each, J = 6.6 Hz, *i*-Pr methyls), 1.4–1.7 (m, 6, methylenes, methines), 1.81–1.85 (m, 2, C-5 Hs), 1.99 (s, 1, H-7), 2.04 (ddd, 1, J = 6, 4, 2 Hz, H-6), 2.07 (d, 1, J = 6 Hz, H-2), 2.24 (dddt, 1, J = 17, 7.5, 3.3, 1.3 Hz, H-4), 2.47 (dddt, 1, J = 17, 11, 8.5, 2.5 Hz, H-4), 4.55, 4.63 (s, 1 each, olefinic Hs); ^{13}C NMR δ 19.5, 19.8 (*i*-Pr methyls), 20.0 (Me), 21.6, (C-9), 22.2 (C-5), 24.2 (C-4), 32.4 (*i*-Pr CH), 36.5 (C-10), 36.6 (C-6), 40.7 (C-7), 42.6 (C-1), 43.6 (C-8), 59.7 (C-2), 105.7 (olefinic CH_2), 151.8 (C-3); exact mass m/e 204.1882 (calcd for $C_{15}H_{24}$ 204.1878).

10α,14-Dehydrocubebene (23) and Phenoxycarbonyl 10ξ-Cubebenyl Sulfide (24). A solution of 104 mg (0.47 mmol) of alcohol **20** in 4 mL of dry THF was added to 25 mg (0.61 mmol) of KH by way of a cannula needle, and the mixture was stirred for 0.5 h. A solution of 0.09 mL (0.64 mmol) of phenyl chlorothionocarbonate in 1 mL of dry HMPA was added and the stirring continued for 1 h. The mixture was diluted with water and ether and worked up in the usual way. A hexane solution of the crude product was kept at –5 °C for 12 h, and the resultant precipitate was filtered. The filtrate was chromatographed (alumina), permitting the isolation (from the early eluates) of 25 mg (26%) of colorless, liquid olefin **23**: IR =CH 3080 (m), C=C 1650 (m), 1635 (m), $R_2C{=}CH_2$ 870 (m) cm^{-1}; ^1H NMR (500 MHz) δ 0.90, 0.94 (d, 3 each, J = 7 Hz, *i*-Pr methyls), 0.9–1.0 (m, 1, H-8), 1.10 (dddd, 1, J = 13, 13, 13, 3.5 Hz, H-9), 1.18 (t, 1, J = 3 Hz, H-6), 1.46 (dddd, 1, J = 12, 6, 6, 3 Hz, H-7), 1.58 (dddd, 1, J = 13, 5, 5, 3.5 Hz, H-8), 1.6–1.7 (m, 1, *i*-Pr CH), 1.7–1.9 (m, 1, H-2), 1.84 (d, 1, J = 3 Hz, H-5), 2.05 (dddt, 1, J = 16, 11, 8, 3 Hz, H-3), 2.1–2.3 (m, 2, H-3, H-2), 2.28 (ddd, 1, J = 14, 4, 3.5 Hz, H-9), 4.65, 4.79, 4.79, 4.79 (br s, 1 each, olefinic Hs); ^{13}C NMR δ 19.4, 20.0 (*i*-Pr methyls), 28.1 (C-8), 28.5 (C-2), 28.9 (C-3), 30.2 (C-6), 32.4 (C-9), 32.9 (C-11), 37.4 (C-1), 42.0 (C-5), 43.5 (C-7), 102.3 (C-15), 104.9 (C-14), 148.9 (C-10), 152.7 (C-4); exact mass m/e 202.1703 (calcd for $C_{15}H_{22}$ 202.1686).

(48) Westfelt, L. *Acta Chem. Scand.* **1967**, *21*, 152.

Crystallization of the solutes of the later eluants from hexane provided 38 mg (22%) of colorless, crystalline ester **24**: mp 91–95 °C; IR =CH 3075 (w), C=O 1725 (s), C=C 1650 (m), 1590 (m), R_2C=CH_2 870 (m) cm^{-1}; ^1H NMR (500 MHz) δ 0.94, 0.96 (d, 3 each, J = 7 Hz, *i*-Pr methyls), 1.01 (ddd, 1, J = 15, 12, 2.5 Hz, H-9), 1.02 (br s, 1, H-6), 1.3–1.4 (m, 1, H-7), 1.42 (ddd, 1, J = 12, 6, 1.5 Hz, H-8), 1.57 (d, 1, J = 3 Hz, H-5), 1.67 (ddd, 1, J = 13, 7, 7 Hz, H-8), 1.71 (s, 3, Me), 1.7–1.8 (m, 2, H-2, *i*-Pr CH), 2.05 (dddt, 1, J = 15, 10, 8, 2.5 Hz, H-3), 2.0–2.2 (m, 1, H-2), 2.21 (ddd, 1, J = 15, 15, 7 Hz, H-3), 2.51 (ddd, 1, J = 15, 4, 2.5 Hz, H-9), 4.65, 4.82 (br s, 1 each, olefinic Hs), 7.15 (d, 2, J = 7.5 Hz, ortho Hs), 7.21 (t, 1, J = 7.5 Hz, para H), 7.36 (t, 2, J = 7.5 Hz, meta Hs); ^{13}C NMR δ 19.0, 19.8 (*i*-Pr methyls), 22.1 (C-8), 25.2 (C-14), 28.6 (C-2), 28.7 (C-6), 29.1 (C-3), 32.4 (C-9), 33.3 (C-11), 38.4 (C-5), 41.0 (C-1), 41.9 (C-7), 55.6 (C-10), 102.6 (olefinic CH_2), 121.4 (*o*-C), 125.8 (*p*-C), 129.3 (*m*-C), 150.8 (*ipso*-C), 152.5 (C-4), 168.8 (C=O). Anal. Calcd for $C_{22}H_{28}O_2S$: C, 74.11; H, 7.92. Found: C, 74.01; H, 8.11.

(±)-δ-Cadinene (26). W-2 Raney nickel (ca. 0.5 g, washed with water and with acetone) was deactivated by its suspension in 2 mL of acetone refluxing for 0.5 h. A solution of 26.3 mg (74 μmol) of ester **24** in 1.5 mL of 1:1 acetone–methanol was added to the freshly deactivated nickel, and the stirring mixture was refluxed for 1.5 h. It then was filtered through Celite and the adsorbant rinsed with ether. The combined filtrate and washings were evaporated, and the residue was exposed to silica B Pasteur pipette flash chromatography. Elution with hexane gave 10.2 mg (68%) of colorless, liquid hydrocarbon **26**: IR and ^1H NMR spectrally identical with reported data;[29,30] ^1H NMR δ 0.79, 0.96 (d, 3 each, J = 7 Hz, *i*-Pr methyls), 0.8–2.1 (m, 9, methylenes, methines), 1.65 (br s, 3, 2-Me), 1.67 (br s, 3, 5-Me), 2.52 (br d, 1, J = 8 Hz, H-8a), 2.71 (ddd, 1, J = 12, 4, 3 Hz, H-6), 5.45 (br s, 1, H-1); ^{13}C NMR δ 15.6, 18.4 (*i*-Pr methyls), 21.6 (5-Me), 21.7 (C-7), 23.5 (2-Me), 26.6 (*i*-Pr CH), 26.7 (C-4), 31.9 (C-6 or C-3), 32.3 (C-3 or C-6), 39.4 (C-8), 45.3 (C-8a), 124.3 (C-4a), 124.6 (C-1), 129.9 (C-5), 134.1 (C-2); exact mass m/e 204.1877 (calcd for $C_{15}H_{24}$ 204.1877).

***cis*-8aβ-Methyl-4-methylene-6α-isopropyl-2α-(*p*-tolylsulfonyl)-1-decalone (37).** A 1.6 M hexane solution of *n*-butyllithium (0.20 mL, 0.33 mmol) was added to a refluxing solution of 62 mg (0.166 mmol) of sulfone **30** in 1 mL of dry THF (it instantly turned yellow-brown), and the reaction was quenched with a 5% NH_4Cl solution at the elevated temperature after 1 min. The mixture was extracted with ether and the extract worked up in the usual fashion. MPLC of the crude product and elution with 20:1 hexane–EtOAc provided a viscous oil, whose crystallization from hexane gave 33 mg (53%) of colorless, crystalline ketosulfone **37**: mp 109–112 °C; IR =CH 3070 (w), C=O 1720 (s), C=C 1650 (w), 1615 (m), 1600 (m), SO_2 1325 (s), 1148 (s), R_2C=CH_2 910 (m) cm^{-1}; ^1H NMR δ 0.72, 0.73 (d, 3 each, J = 7 Hz, *i*-Pr methyls), 0.8–2.3 (m, 6, methylene Hs), 1.04 (s, 3, Me), 2.2–2.3 (m, 1, H-4a), 2.42 (s, 3, aryl Me), 3.00 (dd, 1, J = 14, 13 Hz, H-3), 3.08 (dd, 1, J = 14, 8 Hz, H-3), 4.18 (dd, 1, J = 13, 8 Hz, H-2), 4.99, 5.03 (s, 1 each, olefinic Hs), 7.34 (d, 2, J = 8 Hz, meta Hs), 7.93 (d, 2, J = 8 Hz, ortho Hs); NOE experiment, irradiation of the angular methyl group causing H-4a and H-2 signal enhancements of 7 and 20%, respectively; ^{13}C NMR δ 19.5, 19.5 (*i*-Pr methyls), 21.6 (*p*-Me), 25.9 (C-7), 27.0 (Me), 31.1 (C-3), 32.3 (*i*-Pr CH), 33.5 (C-5), 34.1 (C-8), 43.4 (C-6), 50.2 (C-8a), 53.9 (C-4a), 67.8 (C-2), 114.1 (olefinic CH_2), 129.3 (*m*-C), 129.7 (*o*-C), 135.4 (*p*-C), 143.1 (*ipso*-C), 144.8 (C-4), 204.1 (C-1). Anal. Calcd for $C_{22}H_{30}O_3S$: C, 70.55; H, 8.07. Found: C, 70.55; H, 8.05.

6-Hydroxy-α-copaene (38). A solution of 7.0 mg (0.032 mmol) of alcohol **20** and 25 μL of 47% HI solution in 1 mL of benzene was shaken for 45 min and then diluted with ether. The mixture was worked up as always and the crude product submitted to Pasteur pipette flash chromatography with silica B. Elution with hexane removed unwanted material and with 25:1 hexane–EtOAc gave 6.6 mg (94%) of colorless, liquid alcohol **38**: IR OH 3600 (w), 3470 (br w), =CH 3030 (w), C=C 1635 (w) cm^{-1}; ^1H NMR (500 MHz) δ 0.7–2.0 (m, 6, methylenes, methines), 0.80 (s, 3, Me), 0.87, 0.90 (d, 3 each, J = 6 Hz, *i*-Pr methyls), 1.42 (d, 1, J = 2 Hz, H-7), 1.67 (d, 3, J = 2 Hz, 3-Me), 2.10 (s, 1, H-2), 2.18, 2.19 (dd, 1 each, J = 7, 2.5 Hz, C-5 Hs), 5.27 (br s, 1, H-4); ^{13}C NMR δ 16.1 (Me), 20.9, 21.0 (*i*-Pr methyls), 22.2 (3-Me), 23.1 (C-9), 33.4 (C-10), 33.6 (*i*-Pr CH), 39.4 (C-5), 45.9 (C-1), 46.9 (C-8), 50.4 (C-7), 51.0 (C-2), 76.2 (C-6), 118.2 (C-4), 142.8 (C-3); exact mass m/e 220.1821 (calcd for $C_{15}H_{24}O$ 220.1825).

(±)-α-Copaene (2). The same procedure was used for the isomerization of 6.4 mg (0.031 mmol) of olefin **1**. Elution with hexane yielded 2.0 mg of unidentified material and in early fractions 3.0 mg (47%) of colorless, liquid hydrocarbon **2**: IR and ^1H NMR spectrally identical with reported data;[37a,b] ^1H NMR (500 MHz) δ 0.7–1.8 (m, 7, methylenes, methines), 0.78 (s, 3, Me), 0.84, 0.86 (d, 3 each, J = 6 Hz, *i*-Pr methyls), 1.66 (d, 3, J = 2 Hz, 3-Me), 1.67 (s, 1, H-7), 2.09 (dd, 1, J = 6, 2.5 Hz, H-2), 2.1–2.2 (m, 2, C-5 Hs), 5.20 (br s, 1, H-4); ^{13}C NMR δ 19.1 (Me), 19.6, 19.8 (*i*-Pr methyls), 21.7 (C-9), 23.0 (3-Me), 29.6 (C-5), 32.1 (*i*-Pr CH), 36.1 (C-10), 36.9 (C-6), 39.3 (C-1), 44.2 (C-8), 44.7 (C-7), 54.2 (C-2), 116.0 (C-4), 143.9 (C-3).

6-Hydroxy-1-methyl-8(S^*)-isopropyl-5(R^*)-(*p*-tolylsulfonyl)tricyclo[4.4.0.0^{2,7}]decan-3-one (40). Absolute methanol (8 mL) was added to a solution of 413 mg (1.1 mmol) of olefin **30** in 3 mL of dry CH_2Cl_2, and thereafter ozone was bubbled through the medium at −78 °C until all starting olefin had disappeared (by TLC analysis). The pale purple solution was allowed to warm to room temperature, while nitrogen gas was bubbled through it. Thiourea (42 mg, 0.55 mmol) was added and the mixture stirred for 1.25 h (a precipitate formed during the early part of this period). It was evaporated and an ether solution of the residue was washed with a 5% $NaHCO_3$ solution and processed normally. MPLC of the crude product and elution with 5:1 hexane–EtOAc afforded 343 mg (83%) of colorless, crystalline ketone **40**: mp 135–138 °C (hexane–THF); IR OH 3470 (m), C=O 1725 (s), C=C 1600 (m) cm^{-1}; ^1H NMR δ 0.84 (s, 3, Me), 0.94, 0.99 (d, 3 each, J = 6 Hz, *i*-Pr methyls), 1.5–2.2 (m, 6, methylenes, methines), 2.12 (s, 1, H-2), 2.33 (dd, 1, J = 19, 9 Hz, H-4), 2.47 (s, 3, aryl Me), 2.99 (dd, 1, J = 19, 7 Hz, H-4), 3.26 (s, 1, H-7), 3.56 (dd, 1, J = 9, 7 Hz, H-5), 4.98 (s, 1, OH), 7.40 (d, 2, J = 8 Hz, meta Hs), 7.79 (d, 2, J = 8 Hz, ortho Hs); ^{13}C NMR δ 17.4 (Me), 20.8, 20.8 (*i*-Pr methyls), 21.6 (*p*-Me), 22.0 (C-9), 33.1 (*i*-Pr CH), 33.9 (C-10), 36.1 (C-4), 42.3 (C-7), 45.0 (C-8), 50.3 (C-1), 59.3 (C-2), 61.6 (C-5), 77.8 (C-6), 128.3 (*m*-C), 130.1 (*o*-C), 135.3 (*p*-C), 145.7 (*ipso*-C), 206.7 (C-3). Anal. Calcd for $C_{21}H_{28}O_4S$: C, 66.99; H, 7.50. Found: C, 66.84; H, 7.23.

6-Hydroxy-1-methyl-8(S^*)-isopropyl-4-tricyclo[4.4.0.0^{2,7}]decen-3-one (41). A solution of lithium diisopropylamide (from 1.27 mL (2.04 mmol) of a 1.6 M hexane solution of BuLi and 0.30 mL (2.12 mmol) of dry diisopropylamine) in 3.5 mL of dry THF, kept at −78 °C, was transferred by cannula needle (under positive N_2 pressure) into a solution of 320 mg (0.85 mmol) of sulfone **40** in 5 mL of dry THF at −78 °C. The mixture was stirred for 1 h and the reaction quenched with a 5% NH_4Cl solution. Ether was added and the mixture submitted to the usual workup. MPLC of the crude product and elution with 5:1 hexane–EtOAc produced 173 mg (92%) of enone **41** as a colorless, viscous oil (an analytical sample was prepared by Kugelrohr distillation at 120 °C/0.1 Torr): IR OH 3400 (br m), C=O 1670 (s) cm^{-1}; ^1H NMR δ 0.91, 0.95 (d, 3 each, J = 6 Hz, *i*-Pr methyls), 1.04 (s, 3, Me), 1.5–2.1 (m, 6, methylenes, methines), 2.20 (d, 1, J = 2 Hz, H-2), 3.11 (s, 1, H-7), 5.88 (dd, 1, J = 9, 2 Hz, H-4), 7.24 (d, 1, J = 9 Hz, H-5); ^{13}C NMR δ 17.8 (Me), 20.5, 20.7 (*i*-Pr methyls), 22.7 (C-9), 32.9 (*i*-Pr CH), 34.5 (C-10), 47.2 (C-8), 59.2 (C-7), 62.5 (C-2), 62.7 (C-1), 78.3 (C-6), 124.6 (C-4), 162.7 (C-5), 202.5 (C-3). Anal. Calcd for $C_{14}H_{20}O_2$: C, 76.33; H, 9.15. Found: C, 76.32; H, 9.01.

8-Demethylene-3,8-dioxosativene (42a) and 8-Demethylene-3,8-dioxo-5-episinularene (43a). A mixture of 222 mg (1.01 mmol) of enone **41** and a freshly prepared 1 M methanolic NaOMe solution (0.2 mL) in 10 mL of dry MeOH was stirred at ambient temperature for 35 h. The solvent was evaporated, and the residue was taken up in ether and subjected to the usual workup. MPLC of the crude product and elution with 9:1 hexane–EtOAc provided 175 mg (79%) of colorless, crystalline dione **42a** (Kugelrohr distillation at 80 °C/0.05 Torr was used for the preparation of the analytical sample): mp 40–43 °C; IR C=O 1750 (s) cm^{-1}; ^1H NMR δ 0.92, 0.97 (d, 3 each, J = 6 Hz, *i*-Pr methyls), 1.00 (s, 3, Me), 1.1–1.9 (m, 6, methylenes, methines), 2.04 (d, 1, J = 19 Hz, endo H-2), 2.41 (ddd, 1, J = 19, 5, 1 Hz, exo H-2), 2.43 (br s, 1, H-3a), 2.61 (br s, 1, H-7a), 2.92 (dd, 1, J = 5, 2 Hz, H-1); ^{13}C NMR δ 18.0 (Me), 20.5, 20.9 (*i*-Pr methyls), 24.8 (C-6), 31.5 (*i*-Pr CH), 35.1 (C-5), 40.7 (C-7), 41.2 (C-2), 46.8 (C-7a), 47.3 (C-4), 49.7 (C-1), 64.3 (C-3a), 211.2 (C-3), 218.3 (C-8). Anal. Calcd for $C_{14}H_{20}O_2$: C, 76.33; H, 9.15. Found: C, 75.96; H, 9.29.

Further elution yielded 14 mg (6%) of a 1:1 **42a–43a** mixture and subsequently 7 mg (3%) of colorless, crystalline dione **43a** (analytical sample from Kugelrohr distillation at 80 °C/0.05 Torr): mp 42–45 °C; IR C=O 1750 (s) cm^{-1}; ^1H NMR δ 0.86, 0.97 (d, 3 each, J = 7 Hz, *i*-Pr methyls), 1.10 (s, 3, Me), 1.1–2.0 (m, 6, methylenes, methines), 1.97 (d, 1, J = 19 Hz, endo H-2), 2.29 (br s, 1, H-3a), 2.49 (br s, 1, H-4), 2.55 (dd, 1, J = 5, 2 Hz, H-1), 2.67 (dd, 1, J = 19, 5 Hz, exo H-2); ^{13}C NMR δ 20.0 (Me), 20.5, 21.0 (*i*-Pr methyls), 24.7 (C-6), 29.7 (*i*-Pr CH), 33.3 (C-7), 38.9 (C-2), 39.4 (C-7a), 45.9 (C-5), 48.8 (C-1), 56.3 (C-4), 64.5 (C-3a), 212.4 (C-3), 216.0 (C-8); exact mass m/e 220.1482 (calcd for $C_{14}H_{20}O_2$ 220.1462).

A solution of 3.0 mg (1.4 μmol) of enone **41** and 0.1 mL of concentrated HCl solution in 0.5 mL of methanol was stirred at room temperature for 166 h. Normal workup led to 2.6 mg (88%) of a 3:1 **42a–43a** mixture (by NMR analysis).

8-Demethylene-8-sativone (42c). Dione **42a** (43 mg, 0.20 mmol) was dissolved in 0.17 mL (2.02 mmol) of 1,2-ethanedithiol. A 3.7 M CH_2Cl_2 solution (0.35 mL, 1.3 mmol) of Et_2OBF_3 was added dropwise and the

solution stirred at room temperature for 80 min. It then was diluted with 1 mL of methanol and 15 mL of ether, washed with a 5% NaOH solution, and worked up in the usual way. MPLC of the crude product and elution with 12:1 hexane–EtOAc afforded 52 mg (90%) of colorless, liquid thioketal **42b**: IR C=O 1745 (s) cm^{-1}; ^1H NMR δ 0.89, 0.96 (d, 3 each, J = 7 Hz, *i*-Pr methyls), 1.0–1.8 (m, 6, methylenes, methines), 1.36 (s, 3, Me), 2.24 (d, 1, J = 14 Hz, endo H-2), 2.30 (br s, 1, H-3a), 2.55 (d, 1, J = 6 Hz, H-1), 2.81 (s, 1, H-7a), 2.85 (dd, 1, J = 14, 6 Hz, exo H-2), 3.1–3.4 (m, 4, 2 SCH_2); ^{13}C NMR δ 20.5, 20.5 (*i*-Pr methyls), 20.9 (Me), 24.8 (C-6), 32.1 (*i*-Pr CH), 37.8 (C-5), 38.7, 40.6 (SCH_2), 42.5 (C-7), 49.4 (C-2), 50.7 (C-7a), 51.3 (C-4), 51.8 (C-1), 64.5 (C-3a), 69.6 (C-3), 220.9 (C-8).

A vigorously stirring mixture of ca. 0.5 g of W-2 Raney nickel (washed with water and ethanol) and 34 mg (0.12 mmol) of the thioketal (**42b**) in 2 mL of ethanol was refluxed for 1 h. A second batch of ca. 0.5 g of the nickel was added and refluxing continued for another 1 h (TLC showed the reaction to be complete). The mixture was filtered through Celite and the absorbant rinsed with hot ethanol. The combined filtrate and washings were evaporated, and the residue was submitted to Pasteur pipette flash chromatography on silica B. Elution with hexane removed unwanted material, and elution with 50:1 hexane–EtOAc provided 3 mg of impure, desired product and 15.5 mg (65%) of colorless, liquid ketone **42c**: IR, ^1H NMR and ^{13}C NMR spectrally identical with cited data;[39,49,50] ^1H NMR δ 0.87, 0.92 (d, 3 each, J = 7 Hz, *i*-Pr methyls), 0.98 (s, 3, Me), 1.0–1.9 (m, 10, methylenes, methines), 1.92 (br s, 1, H-3a), 2.21 (br s, 1, H-7a), 2.48 (d, 1, J = 4 Hz, H-1); ^{13}C NMR δ 16.8 (Me), 20.7, 21.0 (*i*-Pr methyls), 21.8 (C-3), 25.3 (C-6), 26.5 (C-2), 32.5 (*i*-Pr CH), 36.3 (C-5), 42.6 (C-7), 48.8 (C-3a), 49.8 (C-4), 50.2 (C-7a), 51.2 (C-1), 223.6 (C-8); exact mass m/e 206.1666 (calcd for $C_{14}H_{22}O$ 206.1670).

8-Demethylene-5-epi-8-sinularone (43c). The **42a** → **42b** reaction procedure (vide supra) was applied to 16.7 mg (0.076 mmol) of dione **43a**, 64 μL (0.76 mmol) of 1,2-ethanedithiol, and 144 μL (0.53 mmol) of a 3.7 M CH_2Cl_2 solution of Et_2OBF_3. Elution with hexane removed unwanted material, and elution with 50:1 hexane–EtOAc gave 16 mg (71%) of colorless, liquid thioketal **43b**: IR C=O 1745 (s) cm^{-1}; ^1H NMR δ 0.83, 1.00 (d, 3 each, J = 6 Hz, *i*-Pr methyls), 1.0–2.2 (m, 8, methylenes, methines), 2.30 (s, 1, H-3a), 2.92 (dd, 1, J = 14, 5 Hz, exo H-2), 2.95 (s, 1, H-4), 3.0–3.4 (m, 4, 2 SCH_2).

The **42b** → **42c** reaction procedure (vide supra) was applied to ca. 0.3 g of W-2 Raney nickel and 16 mg (0.054 mmol) of the thioketal in 1 mL of ethanol. Hexane elution removed unwanted material and elution with 50:1 hexane–EtOAc furnished 8.3 mg (74%) of colorless, liquid ketone **43c**: IR and ^1H NMR spectrally identical with published data;[40] ^1H NMR δ 0.82, 0.96 (d, 3 each, J = 7 Hz, *i*-Pr methyls), 0.99 (s, 3, Me), 1.1–2.1 (m, 10, methylenes, methines), 1.70 (br d, 1, J = 4 Hz, H-1), 2.05 (br s, 1, H-3a), 2.17 (br s, 1, H-4); ^{13}C NMR δ 19.8, 20.1 (*i*-Pr methyls), 21.2 (Me), 24.7 (C-3), 25.2 (C-6), 25.6 (C-2), 29.6 (*i*-Pr CH), 34.0 (C-7), 47.3 (C-7a), 47.5 (C-5), 50.0 (C-3a), 55.7 (C-1), 57.3 (C-4), 221.5 (C-8); exact mass m/e 206.1675 (calcd for $C_{14}H_{22}O$ 206.1670).

1-Methyl-8(*S)-isopropyl-4-tricyclo[4.4.0.0^{2,7}]decene-3(*S**),6-diol (46a) and Its 3(*R**) Epimer (46b).** $NaBH_4$ (14 mg, 0.36 mmol) was added to a solution of 80 mg (0.36 mmol) of enone **41** and 135 mg (0.36 mmol) of $CeCl_3 \cdot 7H_2O$[51] in 2.5 mL of methanol and the mixture stirred for 5 min. It was diluted with water and ether and processed in the usual manner. MPLC of the crude product and elution with 4:1 hexane–EtOAc afforded 59 mg (73%) of colorless, crystalline diol **46a**: mp 109–112 °C; IR OH 3600 (m), 3440 (br w), =CH 3040 (w), C=C 1635 (w) cm^{-1}; ^1H NMR δ 0.88, 0.91 (d, 3 each, J = 6 Hz, *i*-Pr methyls), 1.07 (s, 3, Me), 1.5–2.0 (m, 7, methylenes, methines), 2.26 (s, 1, H-7), 4.34 (br s, 1, H-3), 5.68 (dt, 1, J = 9, 3 Hz, H-4), 5.98 (d, 1, J = 9 Hz, H-5); ^{13}C NMR δ 18.3 (Me), 20.6, 20.8 (*i*-Pr methyls), 22.9 (C-9), 33.1 (*i*-Pr CH), 34.5 (C-10), 45.5 (C-1), 47.6 (C-8), 49.8 (C-7), 55.0 (C-2), 71.7 (C-3), 78.0 (C-6), 126.4 (C-4), 142.4 (C-5); exact mass m/e 222.1630 (calcd for $C_{14}H_{22}O_2$ 222.1619).

Further elution yielded 9 mg (11%) of diol **46b** as colorless, viscous oil: IR OH 3600 (m), 3440 (br m), =CH 3040 (w), C=C 1635 (w) cm^{-1}; ^1H NMR δ 0.88 (s, 3, Me), 0.90, 0.95 (d, 3 each, J = 6 Hz, *i*-Pr methyls), 1.5–2.0 (m, 6, methylenes, methines), 1.70 (t, 1, J = 3 Hz, H-2), 2.32 (s, 1, H-7), 4.24 (br s, 1, H-3), 5.65 (dt, 1, J = 9, 3 Hz, H-4), 6.04 (d, 1, J = 9 Hz, H-5); ^{13}C NMR δ 16.4 (Me), 20.6, 20.9 (*i*-Pr methyls), 22.9 (C-9), 33.5 (*i*-Pr CH), 34.3 (C-10), 47.2 (C-8), 47.4 (C-7), 49.6 (C-2), 53.1 (C-1), 69.5 (C-3), 78.3 (C-6), 125.9 (C-4), 143.7 (C-5); exact mass m/e 222.1606 (calcd for $C_{14}H_{22}O_2$ 222.1619).

2,3-Dehydro-8,9-dihydrosativen-8(*S)-ol (49) and 2,3-Dehydro-8,9-dihydro-5-episinularen-8(*R**)-ol (50).** HCl gas was bubbled for 5 s through a solution of 18.7 mg (0.084 mmol) of enediol **46a** in 1 mL of dry methanol. After 2 min the deeply blue solution was diluted with water and subjected to the usual workup. Pasteur pipette flash chromatography of the crude product on silica B and elution with 40:1 hexane–EtOAc furnished 13 mg (76%) of a 3:1 colorless, liquid **47**–**48** mixture (by ^1H NMR spectral analysis): IR and ^1H NMR spectrally identical with recorded data;[41,42] IR =CH 3060 (w), C=O 1740 (s), C=C 1568 (w) cm^{-1}; ^1H NMR δ(**47**) 0.87, 0.92 (d, 3 each, J = 6 Hz, *i*-Pr methyls), 1.03 (s, 3, Me), 1.1–1.9 (m, 6, methylenes, methines), 2.37 (br s, 1, H-3a), 2.73 (br s, 1, H-7a), 3.00 (br s, 1, H-1), 6.05 (br t, 1, J = 5 Hz, H-3), 6.60 (dd, 1, J = 5, 3 Hz, H-2), δ(**48**) 0.85, 0.96 (d, 3 each, J = 6 Hz, *i*-Pr methyls), 1.1–1.9 (m, 6, methylenes, methines), 2.27 (br s, 1, H-3a), 2.32 (br s, 1, H-4), 2.66 (t, 1, J = 3 Hz, H-1), 5.98 (br, t, 1, J = 5 Hz, H-3), 6.41 (dd, 1, J = 5, 3 Hz, H-2). The same reaction was performed on diol **46b**, as well as on the **46a**–**46b** mixture, and gave the same results.

A 1.4 M ethereal solution of MeLi (0.27 mL, 0.37 mmol) was added dropwise to a solution of 7.6 mg (37 μmol) of the above **47**–**48** ketone mixture in 0.5 mL of dry ether and the mixture refluxed for 2.5 h. The cooled solution was diluted with wet ether and processed normally. Pasteur pipette flash chromatography of the crude product on silica B and elution with 50:1 hexane–EtOAc (after removal of undesired material by hexane elution) provided 1.7 mg (20%) of colorless, liquid alcohol **50**: IR OH 3610 (w), =CH 3060 (w), *Z*-CH=CH 725 (m) cm^{-1}; ^1H NMR δ 0.87, 0.95 (d, 3 each, J = 6 Hz, *i*-Pr methyls), 0.97 (s, 3, Me), 1.1–2.0 (m, 7, methylenes, methines), 1.17 (s, 3, 8-Me), 1.98 (br s, 1, H-3a), 1.99 (br s, 1, H-1), 5.98 (dd, 1, J = 5, 3 Hz, H-3), 6.16 (dd, 1, J = 5, 3 Hz, H-2); ^{13}C NMR δ 21.7, 21.8 (*i*-Pr methyls), 23.5 (Me), 24.4 (C-6), 29.6 (C-7), 31.5 (8-Me), 32.9 (C-7a), 33.5 (*i*-Pr CH), 46.2 (C-5), 49.0 (C-4), 58.6 (C-3a), 60.7 (C-8), 64.3 (C-1), 134.3 (C-2), 137.5 (C-3); exact mass m/e 220.1819 (calcd for $C_{15}H_{24}O$ 220.1826).

Further elution led to 5.1 mg (62%) of colorless, liquid alcohol **49**: ^1H NMR spectrally identical with data cited in the literature;[42] IR OH 3610 (w), 3480 (br w), =CH 3060 (w), C=C 1578 (w), *Z*-CH=CH 725 (m) cm^{-1}; ^1H NMR δ 0.81 (s, 3, Me), 0.87, 0.89 (d, 3 each, J = 7 Hz, *i*-Pr methyls), 1.08 (s, 3, 8-Me), 1.2–2.0 (m, 6, methylenes, methines), 1.96 (br s, 1, H-3a), 2.03 (d, 1, J = 4 Hz, H-7a), 2.39 (br s, 1, H-1), 6.25, 6.26 (s, 1 each, H-2, H-3); ^{13}C NMR δ 21.0, 21.0 (*i*-Pr methyls), 24.0 (Me), 25.8 (C-6), 28.1 (8-Me), 33.2 (*i*-Pr CH), 37.5 (C-5), 43.7 (C-7), 44.0 (C-4), 56.8 (C-7a), 57.8 (C-3a), 60.4 (C-1), 81.8 (C-8), 137.0 (C-2), 139.6 (C-3); exact mass m/e 220.1824 (calcd for $C_{15}H_{24}O$ 220.1826).

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